Space weather and solar storms

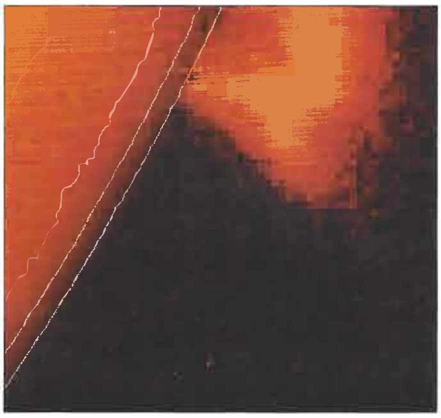
A host of spacecraft monitor activity on the Sun because solar outbursts can have far reaching effects on the Earth. By Alister Graham.

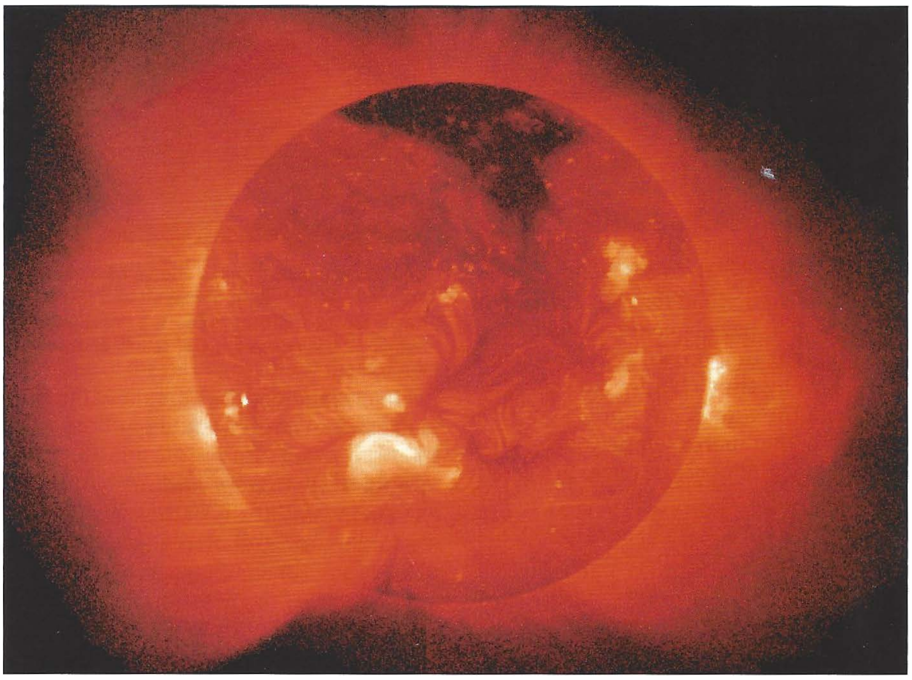
Solar activity is expected to remain at moderate to high levels over the coming days. More M-class, and possibly X-class flares are expected from the vicinity of the northeast limb of the Sun. Due to high solar winds and approaching electron and magnetic clouds, geophysical activity is expected to be unsettled increasing to active levels by tonight. Storm warnings are issued for the high latitudes during the coming period.

Sounding like an excerpt from a science fiction story, this is actually very close to the real 'space weather' reports which are daily and jointly prepared by the U.S. Department of Commerce, the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.S. Air Force and the Space Environment Center. Such reports are issued because 'space storms' from heightened solar activity interfere with radio and satellite communications, can cause disruptions and loss of satellites, endanger the lives of astronauts and passengers on supersonic aircraft, and have led to the failure of power grids at a cost of hundreds of millions of dollars.

Since the last solar maximum in 1989, a suite of satellites have been launched into space which now provide measurements, forecasts and warnings about approaching space weather and space storms from the Sun.

The Yohkoh spacecraft images the great flare of November 2, 1992. The contours show the location of the limb. The flare occurred about ten degrees behind the limb and is one of the largest to be detected by Yohkoh. Image: ISAS and the Yohkoh team.





An X-ray image of the Sun taken by the Yohkoh satellite. Yohkoh is a mission of ISAS, Japan.

The source of space weather

'Space weather' is a collective term used to describe the range of particles and radiation in our Solar System which originate, primarily, from the Sun.

Large enough for one million Earths to fit inside it, the Sun is literally a self-gravitating nuclear reactor. While its average surface temperature is 5770 degrees, with the dark sun spots a thousand degrees cooler, its core temperatures reach tens of millions of degrees.

In addition to the light that is emitted from the Sun, it continuously blows into space a stream of charged particles (mostly electrons and protons); referred to as the solar wind, these particles leave the Sun at speeds of 1-2 million miles per hour. By the time the solar wind reaches the Earth, its typical density has dropped to around eight protons and eight electrons per cubic centimeter; heavier particles exist in smaller numbers but the net electric charge on the solar wind is zero.

This wind is thought to continue out to two and a half times as far as the outermost planet Pluto – that is 100 times further out than the Sun-Earth distance of 150 million kilometres. Less frequent, but more energetic emissions include flares and coronal mass ejections (CMEs) – the expulsion of enormous bubbles of ionised gas (plasma) from ever changing holes in the Sun's outer atmosphere or corona.

CMEs are the most violent explosions in our Solar System. They release energy in excess of that coming from the detonation of one million nuclear bombs, and a single event can eject some ten thousand million tonnes of plasma into space, expanding to a size larger than the Sun in just a few hours. CMEs come in a range of sizes, and during solar maximum about three CMEs per day – not all directed at the Earth – are thrown out by the Sun, some 15 times more frequently than during solar minimum.

While the ultraviolet (UV) and X-ray radiation arrive at the Earth after having left the Sun some eight minutes earlier, plasma travels slower than the speed of light and takes about one to two days to arrive. While typical speeds for the solar wind are less than two million miles per hour, CMEs can reach speeds of up to 4.5 million miles per hour, creating a shock-wave effect as it slams into the slower moving solar wind.

The internal dynamo which powers the magnetic fields in the Sun and is responsible for such solar activity and outbursts is thought to arise from the complex motions of the charged plasma beneath the solar surface. While a convection zone is commonly believed to be an essential component for the dynamo, convection zones are thought to only exist in main sequence stars (that is, stars fusing hydrogen to helium in their cores) with masses less than about 1.5 solar masses.

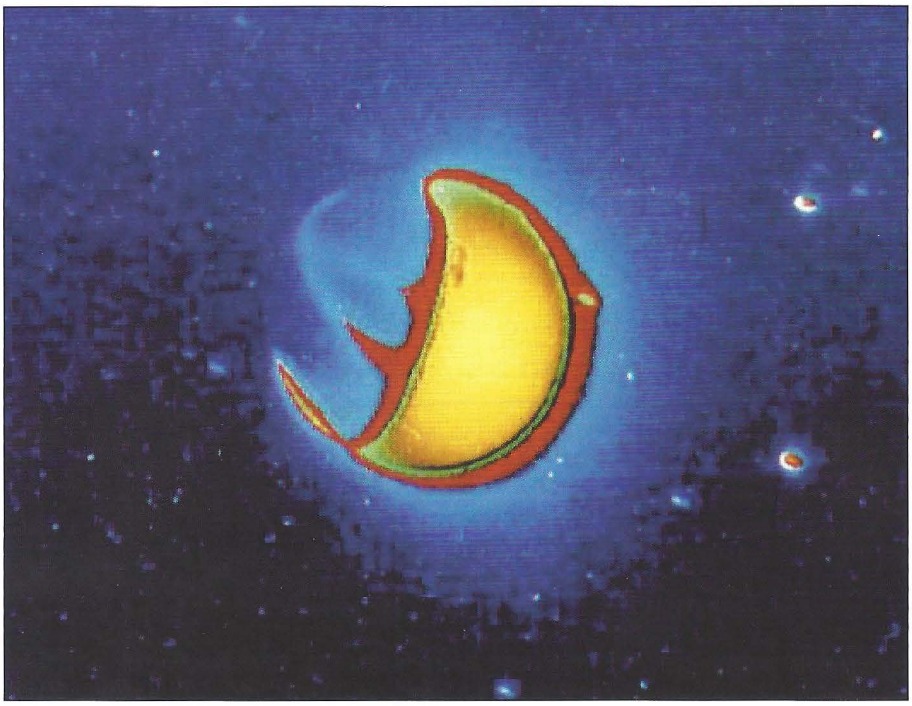
However, the recent discovery by Dr Garik Israelian *et al* of an extended magnetic loop spanning 150 solar radii in the B-type supergiant Rigel (beta Orionis A, the second brightest star in the constellation of Orion) reveals a rotating magnetic field in a star thought not to have a convection zone due to its mass of over ten solar masses. This highlights the concern that the internal processes within stars is not yet fully understood, and that we cannot predict what our Sun may or may not do.

More disturbing still, are the incredibly powerful flares, up to one million times more energetic than flares measured on the Sun, that have been observed in stars very similar to our own (F8-G8 spectral class). Why these 'superflares' do not occur in the Sun is not known. What is known is that increased periods of solar activity does influence our lives in a variety of ways.

Solar activity has been observed for centuries to cycle through periods of maximum and minimum activity in a roughly eleven year period. Driven by differential rotation and convection, at each solar maximum comes the reversal of the Sun's magnetic poles. So while during one particular 11-year cycle magnetic north may point up and magnetic south down, during the next cycle magnetic north will point down and magnetic south will point up. Hence, one complete solar cycle is actually 22 years long.

With this reversal of magnetic poles, odd numbered cycles (the 2000-2001 solar maximum will be cycle 23) are observed to be more energetic than their preceding even numbered cycle.

The interconnection of the Earth's magnetic field with the interplanetary magnetic field allows entry of charged particles and the transfer of energy to the magnetosphere and ionosphere at the Earth's magnetic poles. The interplanetary magnetic field reverses direction with the Sun's magnetic polarity flip. When the interplanetary magnetic field points southward (opposite to the Earth's current magnetic field orientation) the amount of interconnection is at its greatest.



This false colour picture shows how the Earth glows in ultraviolet light taken by the far UV camera/spectrograph deployed and left on the Moon by the crew of Apollo 16. The part of the Earth facing the Sun reflects a great deal of UV light. The side facing away from the Sun shows bands of UV emission, the result of aurora. Image: NASA.

Communication breakdown

The Sun continually bathes our planet in radiation. UV radiation photoionises the outer layers of our atmosphere to produce what is called the ionosphere. In this process, incident UV radiation strikes neutral atoms in the Earth's upper atmosphere, knocking out the outer electrons and leaving the atoms in an ionised state.

Starting at about 50-60 km above the Earth's surface, Mankind has used the ionosphere to reflect radio signals (below about 30 MHz) over vast distances of land and sea. Those frequencies above 30 MHz, including the very high frequency (VHF) and ultra high frequency (UHF) bands, pass through the ionosphere and are therefore useful for satellite communications and broadcasts.

Enhanced solar activity can disturb the ionosphere in a number of ways which interfere with radio and microwave communications. Solar flares can emit large quantities of UV and X-ray radiation which causes a sudden increase in the density of ionized particles in the lower D- and E-regions of the sunlit side of the Earth's ionosphere. Such disturbances last from minutes to hours, corresponding to the lifetime of the flare, and can result in what is known as shortwave fadeout, in which radio signal strength can fade or drop out completely due to increased absorption.

Amateur radio enthusiasts, search and rescue organisations, *Voice of America*, *Radio Free Europe*, many military transmissions and other high frequency radio communications are severely hampered by such events. Additionally, the increased occurrence of electron density irregularities along the ground-to-satellite transmission path results in the higher VHF and UHF frequencies experiencing unpredictable reflections and scattering (scintillation) of the signal phase strength resulting in transmission interference.

Emissions of energetic protons and electrons from the larger flares enter into the Earth's atmosphere and spiral along its magnetic field lines. These particles can collide with electrically neutral atmospheric atoms such as oxygen and nitrogen, imparting energy and 'exciting' the outer electrons. When the excited electrons then drop back down into their more stable configuration, there is an associated emission of a particle of light.

Each particular colour of the light depends on the gas and the energy difference between the excited and stable configuration of the atom involved. The light from oxygen atoms may be either red (630nm) or green (558nm), depending on the energy levels the excited electron dropped between, and is the cause of two of the main colours seen in aurora.

Generally located between latitudes of 60-70 degrees north and south of the equa-

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tor, and at an altitude of 100 to several hundred kilometres, aurorae migrate towards the equator at times of heightened solar activity. Aurorae are also known as the 'northern lights' (aurora borealis) and the 'southern lights' (aurora australis).

Due to the channelling of these charged solar particles along the Earth's magnetic field lines to the magnetic poles, the lower regions of the ionosphere (below 100km) near the poles can become heavily ionised. Short wave fadeout at the poles, known as Polar Cap Absorption (PCA), can become severe and total for periods of days to weeks. During one tense week in November 1960, supply planes were unable to fly to the south pole as they could not obtain any radio assurance of good weather for a safe landing at the McMurdo base camp.

Ground currents

Coronal mass ejections can impact with the Earth and create global disturbances to the Earth's magnetic field. Such disturbances are known as geomagnetic storms and can last from hours to several days. The variable flow of charged particles from the Sun through the Earth's atmosphere are effectively electric currents and associated with them are fluctuating magnetic fields that in turn induce electrical currents across the planet's surface. Given that electricity encounters less resistance when it flows through metal than rock or water, these ground induced currents tend to flow through power lines or pipeline networks that criss-cross the landscape.

Magnetic storms are not a recent phenomenon, and their influence on human technology has been noticed for over a century. During a magnetic storm on February 4, 1872, telegraph communications were actually sent without any local power source; magnetic storm induced currents did the work.

Damage to pipelines is evident through increased levels of corrosion. The labour and resources cost from reduced life-spans of pipes in high latitude regions is significant; especially when you consider, for example, the 2,000 mile long natural gas pipe line across the USA, which has 7,500 miles of branch piping.

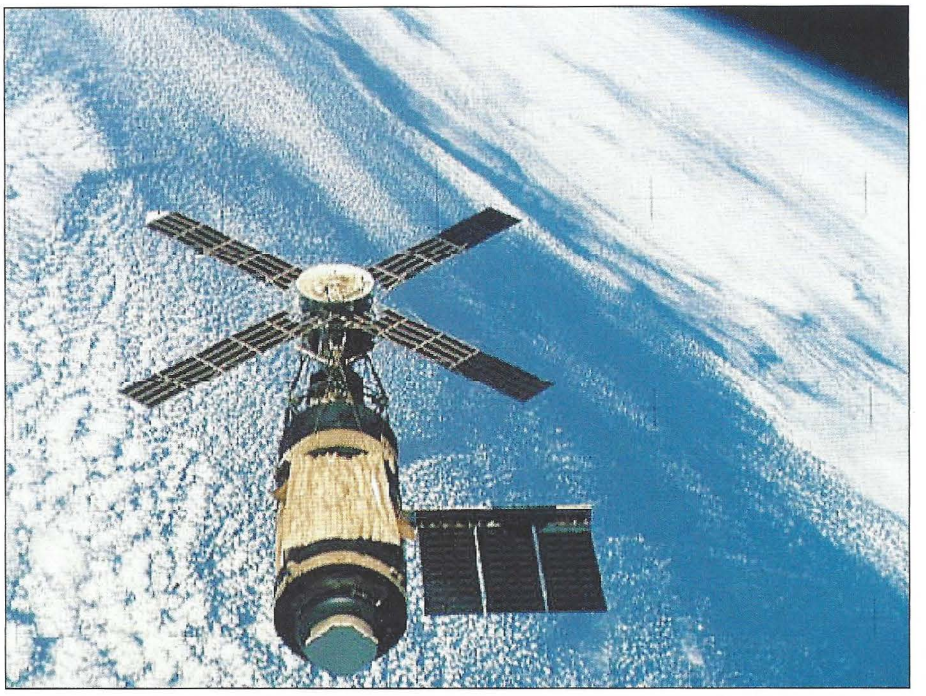
The affects of geomagnetic storms on power-grids are much more dramatic and sudden. On March 13, 1989, seven days after one of the strongest X-ray flares and a host of other activity was observed on the Sun, ground induced currents from geomagnetic storms brought down Canada's entire Hydro Quebec power system in just 90 seconds. The origin of the flare was an impressively large sunspot known as AR5395, it was 54 times larger than the Earth but yet still covered less than one half of a percent of the solar disc.

Transformers which are used to manipulate the current and voltage flows through power-grids are designed to operate with alternating current (AC). Ground induced currents are direct currents (DC) and can, and did, cause the transformers in the Hydro Quebec power system to catch on fire and breakdown. While such transformers alone cost millions of dollars, the total estimated cost of this blackout has been placed at hundreds of millions of dollars.

The same geomagnetic storm was also responsible for power outages in Europe and Central America. Such blackouts can be very dangerous. More than six million Canadians lost electricity for at least nine hours, some for many more. During winter, the loss of heating and other essential services can be life-threatening.

More recently, on October 12 and 13 1999, the Sun threw out three very impressive CMEs. Fortunately they were not directed toward the Earth. As we enter the 2000-2001 solar maximum, many more such outbursts from the Sun can be expected.

In 1999, Dr Richard Canfield and a team of collaborators have identified S-shaped figures, called sigmoids, on the Sun which appear to be the sites for CMEs. The sigmoid structures reveal sheared and twisted solar magnetic filled lines and usually appear a few days before the CME, therefore hopefully giving several days advanced warning.



Skylab was an orbiting laboratory launched in May 1973. It fell back to Earth on July 11, 1979, sooner than expected because of activity on the Sun. Image: Skylab, NASA.

Satellites – a drag

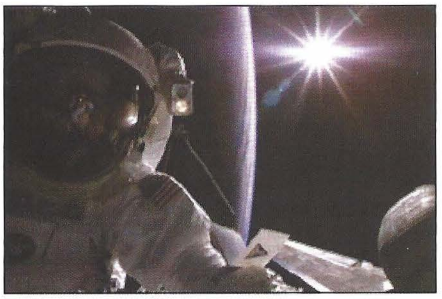
At typical weather satellite orbit altitudes of around 850 kilometres, the mean atmospheric density is around one million particles per cubic centimetre. However, large geomagnetic storms cause heating and expansion of the Earth's atmosphere, and particle densities at satellite altitudes can increase a hundred fold. This results in a significant increased 'drag' (slowing by collisions of the satellite with air particles) on such satellites, and leads to decaying orbits and the satellites start to fall back to Earth.

The increased drag can be sudden and dramatic enough that satellites are temporarily lost by tracking stations as they drop to lower altitude orbits. Some satellites, like the Hubble Space Telescope (HST), require shuttle boosts to keep placing them back into their optimal orbit.

In 1979, NASA's space station SkyLab crashed back down to Earth due to increased levels of atmospheric drag caused by heightened solar activity. Ironically, one of the tasks of SkyLab was to monitor X-ray emission from the Sun. SkyLab burnt up over the Indian Ocean and parts of it crashed down on land, fortunately not in a populated area but in the western Australia outback.

NORAD, the joint US/Canadian military command force responsible for the aerospace defence of North America, track the orbits of thousands of satellites and man-made space debris in Earth orbit. In March 1989, the Solar Maximum Mission (SMM) satellite – put into space to observe the Sun during solar maximum – was

Astronauts are at risk from radiation from the Sun, particularly when working outside. Image: NASA.



reported by NORAD to have "dropped as if it hit a brick wall". Geomagnetic storms were of such strength and so widespread that the dramatic increase in atmospheric drag on satellites increased the number of 'missing' satellites from around 300 to 1300 – the majority of the disappearing objects later found at reduced altitudes.

Satellites – a buzz

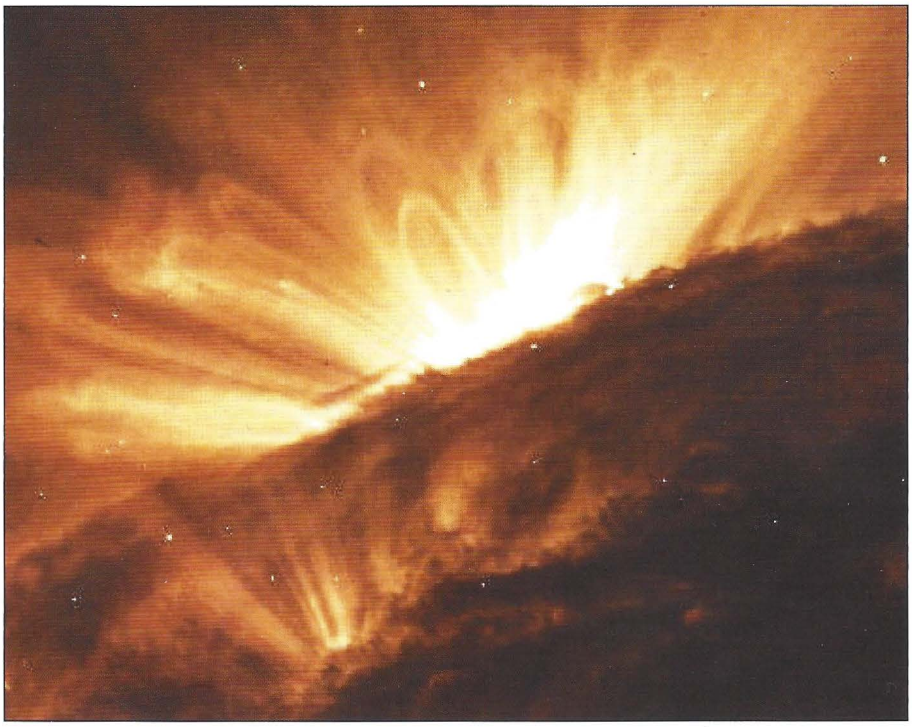
When satellites pass through the auroral zones, the Van Allen belts, or clouds of charged particles in interplanetary space, they can be charged up. Dielectric surfaces can be charged to much higher potentials than the metal surfaces of the satellite, and this can result in unwanted electric discharges that may either damage the material or lead to what is known as 'phantom commands' in the onboard computer systems.

On October 7, 1995, the Intelsat 511 satellite passed through a cloud of high-velocity electrons which resulted in an electrostatic discharge that actually fired the satellites rocket thrusters. The unexpected change to the satellites altitude caused a loss of 'Earth lock' from ground tracking stations.

Phantom commands also resulted in the loss of control of the Canadian telecommunication satellites Anik E-1 and Anik E-2 on January 20 and 21, 1994.

Such undesirable activity is not restricted to satellites in Earth orbits. Due to the location of Jupiter's innermost moon Io, the October 1999 flyby of this moon by NASA's Galilio spacecraft passed through a region of intense radiation from Jupiter. The radiation spawned an error in the onboard computers, causing the spacecraft to place itself in a 'safe mode' and shutdown all non-essential operations. Thankfully, engineers managed to upload new commands that resumed operations of the spacecraft and allowed continued transmission of images and data back to Earth while avoiding use of the damaged portion of the computer's memory.

In such environments, highly energetic particles can enter into computer chips and memory cells, corrupting stored information and burning out circuits. Such particles also smash into the crystal arrays of the semiconductor material used for solar panels and degrade the effectiveness of the solar cell. The solar panels from one of the Geostationary Operational Environmental Satellites (GOES) had six years of operating lifetime eroded away in just a few days during the 1989 solar maximum.



This dramatic high resolution picture looking across the edge of the Sun was taken by a telescope on board the Transition Region and Coronal Explorer (TRACE) satellite. It shows graceful arcs of intensely hot gas suspended in powerful looping magnetic fields above a solar active region. Image: NASA.

Space weather satellites

Space weather monitoring and forecasts are immediately useful for those who provide communication services, the power industries, satellite and shuttle operators, space station builders, geomagnetic surveys for the exploration of natural resources, range-finding and navigational systems, and those operating space probes to other planets or those select few on the surface of the Moon or Mars.

Passengers in high-altitude aircraft also benefit from advanced warning of dangerous particle emissions from the Sun. Flights over and near the poles, such as the supersonic flights, can be avoided or reduced in order to minimise radiation exposure to flight crew and passengers. Given that radio and satellite communications and electricity are used in our everyday lives, a reliable monitoring service is in all our interests.

Radiation exposure to astronauts is a real threat. On August 5, 1972, fortunately between the Apollo 16 and 17 manned space flights, one of the largest outbursts of protons from the Sun was measured. If any astronauts had been beyond the Earth's protective magnetosphere at this time, perhaps on their way to the Moon or back, they would have received lethal doses of radiation. Today, most manned missions occur beneath the intense Van Allen radiation belt, and also avoid a region over the south Atlantic near South America where a local weakness in the Earth's magnetic field results in the radiation belts residing at particularly low altitudes.

However, the continued building of the International Space Station into the approaching solar maximum poses a risk for the astronauts, especially as the Space Station orbit is sufficiently inclined from the equator so as to bring the astronauts into the danger zones during geomagnetic storm periods. Advanced warning systems are crucial to get the astronauts either inside some specially designed shielding on the Space Station or back down to Earth.

Many groups from countries around the world, including Australia, France and America, now provide forecasts of solar activity. To give just one example, NASA's Advanced Composition Explorer (ACE) satellite, positioned one million miles upstream from the Earth, provides an hour's warning of approaching particles and radiation that are likely to cause geomagnetic storms here on Earth. A real time solar wind forecast can be viewed at **http://sec.noaa.gov/ace/ACErtsw_home.html.**

NASA also have an extensive website with near real time images, movies and data about the Sun and space weather: **http://www-istp.gsfc.nasa.gov/istp/events/monitor/**

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Dr Alister Graham works as an astronomer at the Instituto de Astrofísica de Canarias in the Spanish Canary Islands where he also provides telescope support for the British Isaac Newton Group of telescopes.