INTERNATIONAL LIVING WITH A STAR

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ABSTRACT

The response of our space environment to the constantly changing Sun is known as "Space Weather". Sudden ejections of plasma and magnetic field structures from the Sun's atmosphere called coronal mass ejections (CMEs) together with sudden bursts of radiation termed solar flares all cause space weather effects at the Earth. The International Living With a Star (ILWS) programme is a space weather focused and applications driven research programme. Its goal is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society. Recent large solar storms caused damages to power systems and satellites and disturbed important navigation and communication systems. Furthermore, accurate monitoring of the energy output from the Sun is important for understanding how the Sun contributes to the observed warming of our planet. The Sun is a variable star we better learn how to live with.

1. INTRODUCTION

For thousands of years people in the north marvelled at the space weather seen in the Northern Lights. But auroras never hurt a salmon or farmer. It is only with our modern electrical, electronic and space technologies that the Sun's effects become damaging, and even personally hazardous for astronauts. The more we do in space, the more serious and potentially costly the problems will become.

The response of the space environment particularly around the Earth to the constantly changing Sun is known as 'space weather'. Most of the time space weather is of little concern in our everyday lives. However, when the space environment is disturbed by the variable outputs of the Sun, technologies that we depend on can be affected.

The increasing deployment of radiation-, current-, and field-sensitive technological systems over the last few decades and the increasing presence of complex systems in space, combine to make society more vulnerable to solar-terrestrial disturbances. This has been demonstrated by the large number of problems associated with the severe magnetic storms between 1989 and 1991 and more recently during the the maximum of cycle 23.

Figure 1: Composit image presenting the most visible elements of space weather: a storm from the Sun, aurora as seen from space, and aurora as seen from the Earth. The solar storm is a corona mass ejection (CME) composite from EIT 304Å superimposed on a LASCO C2 image, both from SOHO. The middle image from Polar's VIS imager on July 14, 2000. Lastly, aurora over Alaske (Ian Curtis)

2. THE ACTIVE SUN

Space weather disturbances are generally caused by transient events in the solar atmosphere. There are two different types of events which triggers disturbances in the Earth's environment. One type is called a solar flare because the brightening of a small area on the Sun heralds its occurrence. However, not all solar flares result in geomagnetic storms, and, even more significantly, not all geomagnetic storms can be associated with solar flares. Some of the most dramatic space weather effects occur in association with eruptions of material from the solar atmosphere into interplanetary space. These eruptions are known as coronal mass ejections, or CMEs. Such eruptions are sometimes associated with flares and sometimes not, and they now appear to be a primary cause of geomagnetic activity.

The emission from the two types of disturbances can be divided into two classes, electromagnetic radiation and particles which will have different effects on the Earth's environment, as discussed below.
2.1 Particle radiation

A continuous flow of charged particles (protons and electrons) is streaming out from the Sun and is called the solar wind. Several types of solar events can cause particles with high velocities to be superimposed on this background solar wind. CMEs are believed to be caused by sudden disruptions in the Sun's magnetic field. These magnetic fields stretch and twist like titanic rubber bands until they snap. A large CME can contain 1000 million tons of matter that can reach speeds at the Earth up to 2000 kilometres per second, considerably greater than the normal solar wind speeds of about 400 kilometres per second. Thus, unlike the solar flares which emit enhanced UV/X-ray radiation, CMEs result in "clouds" of charged particles (ions and electrons). These clouds often bring with them parts of the solar magnetic field and are often named magnetic clouds. The charged particles and the magnetic fields will interact with the Earth's magnetic field when the magnetic clouds reach the Earth's orbit. This results in a disturbance of the Earth's magnetic field and the auroral particle precipitation into the atmosphere increases. The aurora is a dynamic and delicate visual manifestation of solar-induced geomagnetic storms.

The enhanced particle density within the Earth's magnetic fields during a geomagnetic storm can also cause damages to satellites. Less energetic particles contribute to a variety of spacecraft surface charging problems, especially during periods of high geomagnetic activity. In addition, energetic electrons responsible for deep dielectric charging can degrade the useful lifetime of internal components.

Under some conditions solar eruptions can also accelerate charged particles with high energies (protons and heavy particles such as helium). These highly energetic particles can penetrate to electronic components, causing bit-flips in a chain of electronic signals that may result in spurious commands (phantom commands), appearing to spacecraft systems as being sent from the ground control. In addition one can experience erroneous data from the onboard instruments. These spurious commands have caused major failures to satellite systems, even causing the craft to point away from the earth direction. Energetic solar protons are also a radiation health hazard for astronauts on manned space flights. In addition the radiation exposure to passengers in high-altitude aircraft is a concern.

2.2. Electromagnetic Radiation

Less than one percent of the Sun's total emitted electromagnetic radiation lies in the EUV/X-ray and radiowave regions. Still we have a twofold problem. First, solar activity can cause the amount of EUV/X-ray emission to be enhanced by a factor of 100, and radiowave emission by a factor of tens of thousands, over the normal solar output at these wavelengths. Second, it is exactly these wavelengths to which the many radar, communications, and space systems are most vulnerable.

The energetic radiation bursts from flares travel at the speed of light, and so arrive at Earth just eight minutes after leaving the flare site, well ahead of any particles or coronal material also associated with the flare. Moreover, unlike the electrons and ions of the solar wind plasma and the solar energetic particle populations, the passage of electromagnetic waves is not affected by the presence of Earth's magnetic field. The direct response of the upper atmosphere to a burst of solar flare ultraviolet and x-ray emissions is a temporary increase in ionization (as well as temperature) in the sunlit hemisphere lasting from minutes to hours and called a sudden ionospheric disturbance (SID).
In general the geomagnetic storms and increased solar ultraviolet emission heat the Earth's upper atmosphere, causing it to expand. The heated air rises, and the density at the orbit of satellites up to about 1000 km from the Earth increases significantly. This results in increased drag on satellites that may alter an orbit so that the satellite is temporarily "lost" to communications links. Several kilometres drop in altitude has been observed in connection with one single solar event. At times, these effects may be sufficiently severe as to cause premature re-entry of orbiting objects, such as Skylab in 1979 and Solar Maximum Mission in 1989. Unless low-Earth-orbit satellites are routinely boosted to higher orbits, they slowly fall, and eventually burn up in Earth's atmosphere.

Listed below are a variety of effects on Earth from solar particles other than those mentioned above:

- Effects of oil/gas pipelines: Space weather-induced currents similarly flow in long conductors on the ground such as oil pipelines. These currents create galvanic effects that lead to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage.

3. SPACE WEATHER FORCAST

Today our society is much more sensitive to space weather activity than was the case during the last solar maximum in 1991. An example is the possible disruption of satellites. Our society depends on satellites for weather information, communications, navigation, exploration, search and rescue, research, and defense systems. Thus, the impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate. Furthermore, safe operation of the International Space Station depends on timely warnings of eruptions on the Sun.

It is therefore important to forecast and warn about major solar storms. The presence of two satellites located in the L1 Lagrangian point, SOHO and ACE, has definitely improved the accuracy of space weather forecasts. SOHO has several times demonstrated its leading role in the early-warning system for space weather. It provides a continuous real-time monitoring of solar eruptions that affect the Earth's environment and space weather forecast operations have become to rely on SOHO on a routine basis.

3.1. The SOHO Spacecraft

The SOHO mission is a major element of the International Solar Terrestrial Programme (ISTP), and, together with Cluster, forms the Solar Terrestrial Science Programme (STSP), the first cornerstone in ESA's long-term science programme 'Horizons 2000'. ESA was responsible for the spacecraft's procurement, integration and testing. It was built in Europe by an industry team lead by Matra Marconi Space (now called EADS Astrium). Weighing in at 1,850 kg, the SOHO spacecraft measures about 9.5 m across with its solar panels extended and is 4.3 m high. Figure 1 provides a schematic view of the SOHO spacecraft. NASA provided the launcher, launch services and groundsegment system and is responsible for in-flight operations. Mission operations are conducted from NASA/Goddard Space Flight Center (GSFC).

SOHO was launched by an Atlas II-AS from Cape Canaveral on 2 December 1995 and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996, six weeks ahead of schedule.
Commissioning of the spacecraft and the scientific payload was completed by the end of March 1996. The launch was so accurate and the orbital manoeuvres were so efficient that enough fuel remains on board to maintain the halo orbit for several decades, many times the lifetime originally foreseen. An extension of the SOHO mission for a period of five years beyond its nominal mission duration (2 years), i.e. until March 2003, was approved in 1997 by ESA's Science Programme Committee (SPC). A second extension of another four years, i.e. until March 2007, was granted by the SPC in 2002. This will allow SOHO to cover a complete 11-year solar cycle.

4. SOHO - A SPACE WEATHER WATCHDOG

Observations of the solar corona with the Large Angle Spectrometric Coronagraph (LASCO) and the Extreme ultraviolet Imaging Telescope (EIT) instruments on SOHO provide an unprecedented opportunity for continuous real-time monitoring of solar eruptions that affect space weather. Coronal mass ejections (CMEs) are one of the most energetic and important solar phenomena. They propel plasma at speeds up to 2500 km/s into the heliosphere, causing space weather effects here on Earth. These events were first discovered in 1972 by the OSO-7 spacecraft [Tousey, 1973] and later observed with the ATM coronagraph on Skylab, the Solwind coronagraph on the P78-1 satellite and by the Coronagraph/Polarimeter on Solar Maximum Mission (SMM). CMEs have also been observed from ground-based coronagraphs. The most comprehensive monitoring of CMEs is from the LASCO instrument on SOHO.

4.1. LASCO and EIT

LASCO takes images of the solar corona by blocking the light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. CMEs moving outward from the Sun along the Sun-Earth line can, in principle, be detected when they have expanded to a size that exceeds the diameter of the coronagraphs occcluding disk. CMEs directed toward or away from the Earth should appear as expanding halo-like brightenings surrounding the occulter, so-called halo CMEs. LASCO best observes limb CMEs, but its extreme sensitivity even allows unprecedented detection of halo CMEs. EIT provides images of the solar atmosphere at four extreme ultraviolet wavelengths and reveals flares, dimmings and other associated events in the atmosphere. EIT can usually determine whether CMEs seen by LASCO originated on the near or far side of the Sun, based on the presence or absence of corresponding events on the near side.

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4.2 SOHO’s role at the Space Environment Center

The Space Weather Operations Center at the Space Environment Center (SEC) in Boulder uses SOHO images daily. The forecasting operations have come to rely on SOHO on a routine basis as a key input. LASCO provides the only direct observation of coronal mass ejections. Prior to LASCO they had to rely on activity they knew to be well associated with CMEs, but none of these associations are reliable. They use direction, size and velocity information from LASCO images to help determine the arrival time and effectiveness of the disturbance.

EIT also plays an important role at SEC to pin down the source of any eruption. In addition EIT is a very good source for identifying erupting prominences and to identify coronal hole locations. Coronal holes have become an increasingly important part of the geomagnetic forecasting process. In fact at this point in the solar cycle, coronal hole activity has become the predominant driver of geomagnetic activity.

Finally, forecasters use the MDI data on SOHO in order to track sunspot growth and decay and the magnetograms are used to track magnetic field strengths and complexity, a valuable input for flare forecasting.

5. SOHO – PROMOTING SPACE WEATHER TO THE PUBLIC

Late October 2003, SOHO appeared to be in everyone’s focus as the Sun turned from an almost spotless orb into an ominously scarred source of mighty fireworks in just a few days. Around 17 October 2003, solar activity was very low. The face of the sun was nearly blank with only a few tiny sunspots. This was not unexpected: Solar maximum was in 2001, and solar activity had been declining in line with expectations since then.

What happened next may go into the history books as one of the most exciting times for scientists observing the Sun with modern space-based instruments. First, sunspot region 10484 rotated into view, growing fast. It soon caught the attention of sunwatchers around the world. The sunspots in the region covered more than 1700 millionths of the visible solar surface, or 10 times the entire surface of the Earth!

Figure 5: Three unusual large sunspots easily observable with the naked eye in October 2003 (MDI/SOHO)

SOHO scientists already suspected, however, that more trouble was coming around the corner. Region 10486 was rotating onto the solar disk, showing even more signs of activity. And this particular region had caught the attention of solar physicists while it was still on the far side of the Sun! Using a technique known as helioseismic holography, the MDI instrument is routinely used to construct maps of magnetic activity on the far side of the Sun. The far side images had shown considerable strengthening of this region over a short period of time. And it did not disappoint while traveling across the visible disk: By 31 October 2003, its sunspot area had grown to over 2600 millionths, or 15 times the entire surface of the Earth. It was now officially the largest sunspot region of this solar cycle (see Figure 4).

In the mean time, the new region 10488 had grown from nothing into 1750 millionths in just a few days, right in front of the eyes of the world.

Ten X-class flares were registered from the three regions on their journey to the limb. Some flares grabbed worldwide attention when Earth’s regional power distribution systems went on high alert for the impact of associated coronal mass ejections.

Just as solar scientists were ready to start breathing normally again, with the last of the three regions (10486) disappearing behind the solar limb, yet another mega-flare erupted. This one saturated the X-ray detectors on the NOAA’s GOES satellites; the jury was therefore out for a while on the definitive classification of the flare. The GOES X-ray monitor saturates at X17.3, but after a day of analyzing the data, NOAA’s Space Environment Center estimated the event to be an X28 flare. In other words, the strongest X-ray flare ever
recorded since X-ray observations were initiated from satellites in the mid 70's. The three giant sunspots unleashed eleven X-class flares in only fourteen days—equaling the total number observed during the previous twelve months. Two of the other flares went to the top 20 strongest flares. Two of the events also had CMEs moving with speeds exceeding 8 million kilometres per hour, reaching Earth in less than 20 hours. This is almost 5 times faster than typical, and makes them some of the fastest CMEs recorded, close to the record super storm in 1859 [Tsurutani et al. 2003].

One of the magnetic clouds slammed into Earth's magnetosphere on 29 October 2003, creating a G5 geomagnetic storm, the strongest category. Some of these storms created a beautiful aurora as far south as Spain and Florida. Satellites, power grids, radio communication and navigation systems were significantly affected. Airline passengers reported bright auroras on most night flights. A Japanese satellite was lost completely while a number of others experienced problems. Several thousand people lost power in the Southern part of Sweden. Air traffic control moved transatlantic flights further south to avoid loss of radio communication. Climbers in the Himalayas experienced problems with their satellite phones. These are just a few of the effects on our society from these storms [Webb and Allen, 2004].

Six distinct proton events were detected during this stormy period. The largest was a 29,500 Particle Flux Units (1 pfu = 1 p cm⁻² sr⁻¹ s⁻¹), greater than-10-MeV proton event. This severe storm was the second largest proton event in this cycle, and ranks fourth in the all-time list dating back to 1976. The Bastille Day proton event of July 14, 2001 reached 24,000 pfu [SEC, 2004].

The events caused unprecedented attention from the media and the public. Images from SOHO and quotes from SOHO scientists appeared in nearly every major news outlet. Stories including SOHO images were featured on the front page in most newspapers around the world. NASA TV estimated that the story reached "all" newspapers and 2000 US TV channels. This made a significant impact on the awareness of space weather effects in our society. The attention wiped out all existing SOHO web traffic records (requests/data volume): Monthly (31 million/4.3 TB), weekly (16 million/2.6 TB), daily (4.8 million/0.7 TB), and hourly (0.4 million/33 GB). The daily and hourly record volumes were bandwidth limited.

6. SOLAR VARIABILITY AND CLIMATE CHANGE

For more than a hundred years there have been reports of an apparent connection between solar activity and Earth's climate. Solar activity is now known far back in time due to the production of isotopes in the atmosphere by galactic cosmic rays. From such records there is a striking qualitative agreement between cold and warm climatic periods and low and high solar activity during the last thousand years. Whether the recently measured global warming trend is dominated by anthropogenic effects or has a significant or even dominant solar component is not yet fully understood.

Numerous attempts have been made over the years to link various aspects of solar variability to changes in the Earth's climate. Since the Sun's output of electromagnetic radiation and energetic particles varies, and since the Sun is the ultimate driver for the climate system, it seems natural to link the two together and look for the source of climate variability in the Sun itself. In the mid seventies it was pointed out the rough coincidence between the cold period of the so-called Little Ice Age in the late 17th and the early 18th centuries and the Maunder Minimum of sunspot activity, when no sunspots were detected for a period of about 45 years. Radiocarbon records was also used to show that there was also a rough coincidence between earlier periods of warmth and cold in the northern hemisphere and periods of unusually high and low solar activity respectively. He suggested that the cause might lie in the variations in the Sun's total radiative output (the solar "constant"). In recent years there has been a growing concern about the possible anthropogenic forcing of climate change through the increasing atmospheric content of greenhouse gases. This has made the connection between solar variability and global climate change a very controversial research area.

There are basically three ways the Sun could contribute to climate changes.

- A change in the solar total (wavelength-integrated) irradiance.
- A change in ultraviolet irradiance, which modulates the temperature, chemistry, and dynamics in the Earth's atmosphere.
- Direct and indirect influence by solar and cosmic ray particles modulated by the solar wind and the Sun's magnetic field.
The climate of the future will be the sum of man-made and natural variations, but the man-made part cannot be estimated reliably until the contributions of natural agents (Sun, volcanoes, El Nino) have been defined, and subtracted from the observed changes of the past 100 years.

Most of the current climate models only include the direct solar forcing from changes in the total irradiance. Much work needs to be done on this topic and we need to monitor both the Sun and atmospheric parameters such as clouds, ozon, circulation patterns etc. over several solar cycles to better understand the apparently complex amplifying mechanisms that takes place. Satellites will play an important role and several planned missions will focus on these topics.

7. INTERNATIONAL LIVING WITH A STAR

A new international cooperative program in solar-terrestrial physics, the International Living With a Star program (ILWS), has been established to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. ILWS follows the highly successful International Solar Terrestrial Physics (ISTP) program, which has involved partners from Europe, Japan, Russia, and the United States. ISTP, with its steady flow of discoveries and new knowledge in solar-terrestrial physics, has laid the foundation for the coordinated study of the Sun-Earth system as a connected stellar-planetary system, the system that is humanity’s home.

The scientific goal of the ILWS program is to increase our understanding of how solar variability affects the environment on Earth and other planets, both in the short and long term. Of particular interest of the ILWS program are those aspects of the Sun-Earth system that have consequences for life and society. Over the next decade, the ILWS program will assemble the largest fleet of spacecraft ever focused on a single scientific goal.

The objectives of the ILWS program are to:

- Study the connected Sun-Earth system and the effects that influence life and society
- Stimulate international collaboration among potential partners in solar-terrestrial space missions
- Coordinate international research in solar-terrestrial studies, including all relevant data sources as well as theory and modelling; and
- Provide open access to all scientific data and results.

In addition to this initiative, which so far involves the U.S. National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Canadian Space Agency (CSA), Japanese Institute of Space and Astronautical Science (ISAS), and the Russian Aviation and Space Agency (Rosaviakosmos), other nations are conducting scientific research in this field. Planned future international missions include SOLAR-B (2006), STEREO (2006), Solar Dynamics Observatory (2007), Solar Orbiter (2011+), Solar Probe, and Solar Sentinels.

In the years ahead, portions of this spacecraft fleet will be configured into constellations - smart, strategically-located satellites that can work together to provide the timely, on-demand data and analysis to users who enable the practical benefits for scientific research, national policymaking, economic growth, hazard mitigation and the exploration of other planets in this solar system and beyond.

8. REFERENCES

