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What is Space Weather?

Introduction

According to the US National Space Weather Programme (1995, 2000) space weather is defined as "conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health". As our society becomes increasingly dependent on advanced technology systems, we become more vulnerable to the malfunctions of these systems. Sophisticated technology has reduced society's risk from many natural disasters and increased safety and comfort in life, but through its own vulnerability, it has increased the risk of disturbances of the Earth's environment that originate on the Sun.

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For that reason, research on space weather is rapidly expanding. The main goals of space weather research are: (1) improvement of our understanding of the physical processes that shape solar-terrestrial relationships, (2) improvement of the empirical and physics-based models that can be used in forecasting, (3) development of tools to provide necessary data as the input for models.

In this article, intended for non-specialists, I will try to explain briefly what space weather is and why research in this area is so important. For those readers who are interested, a more complete review of space weather achievements and goals can be found in the references.

Solar effects on the Earth's environment

Earth does not float in empty space, but is immersed in the escaping outer atmosphere of the Sun (Figure 1). This 'solar wind' consists of ionized particles, mostly protons and electrons with a small admixture of helium ions. The density of solar wind is low, about 10 particles per cc. Solar wind also carries the Sun's magnetic field, which at the Earth's orbit has a strength of only a few nT, i.e. about 3000 times less than the magnetic field at the Earth's surface. The wind speed at the Earth's orbit is about 450 km/s or more. On its way the solar wind encounters the Earth's magnetic field, which deflects the particles and shields the Earth from the direct effects of the solar wind.

In the absence of solar wind the geomagnetic field can be approximated by a dipole field with an axis tilted about 11 degrees from the spin axis. The force of the solar wind modifies this field, creating a cavity called the magnetosphere. The boundary between the geomagnetic field and solar wind, the magnetopause, is located at a distance of about 10 Earth's radii from the Earth's centre, but can move closer during high solar activity periods. In the anti-sunward direction the magnetosphere is extended into a long (~ 80 Earth' radii) tail, the magnetotail, filled with magnetic field lines that connect to the polar regions of the Earth. At the low-altitude limit, the magnetosphere ends at the ionosphere. The magnetosphere is filled with plasma that originates both from the ionosphere and the solar wind.

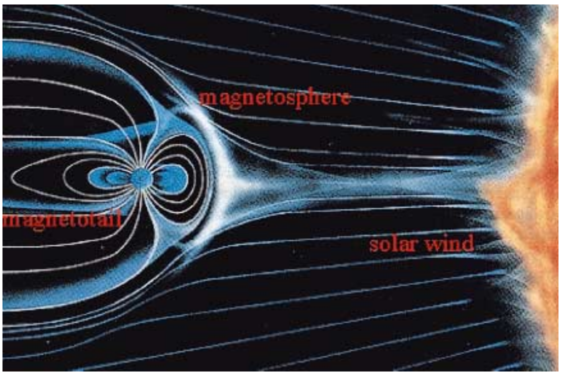

Figure 1. Solar wind overflowing the Earth's magnetosphere. (From Meteorology Today by C. Donald Ahrens © 1994 West Publishing Company)

The Sun is not a quiet, steady star, but undergoes considerable changes, sometimes extremely violent ones. These changes are transferred by the solar wind to the Earth and disturb its magnetic field. The regular changes in the level of solar activity over long-periods are known as the solar cycle. The duration of the solar cycle varies between 9.5 and 11 years. Usually, solar activity is measured by the number of sunspots on the solar surface (Figure 2). The solar cycle is also seen in the number and strength of the solar flares – tremendous explosions, in a localized region on the Sun. In a matter of just a few minutes they heat material to many millions of degrees and release as much energy as a billion megatons of TNT.

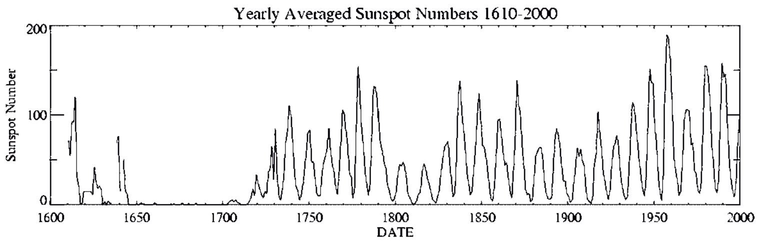

Figure 2. Yearly averaged sunspot numbers from 1610 to 2000. Note a virtual absence of sunspots from 1645 to 1715. This period is called the Maunder minimum or little ice age. (http://www.spaceweather.com/glossary/sunspotnumber.html)

The coronal mass ejections (CMEs) are yet another manifestation of solar activity. Coronal mass ejections are huge bubbles of gas threaded with magnetic field lines that are ejected from the Sun over the course of several hours. CMEs sometimes have higher speed, density and magnetic field strength than is typical of the solar wind and disrupt its flow producing disturbances that strike the Earth with sometimes catastrophic results. Large CME can contain a billion tons of matter that can be accelerated to many tens of MeV. The coronal mass ejection on April 7th, 1997 as observed by the SOHO spacecraft is shown in Figure 3. The structure travelled with a speed of 700 km/s. On April 11th, at 3 o'clock universal time, the ground-based magnetometers recorded the sudden commencement of a severe magnetic storm. On the same day an aurora was observed in the northern part of the United States.

More recently, on October 29th, 2003, a huge CME reached the Earth, following a series of intense solar flares detected one day earlier. The CME had a speed well over 1500 km/s. The magnetic storm associated with this CME was one of the strongest ever observed. After one solar rotation lasting 27 days, the active region reappeared on the solar disk again initiating an intense magnetic storm.

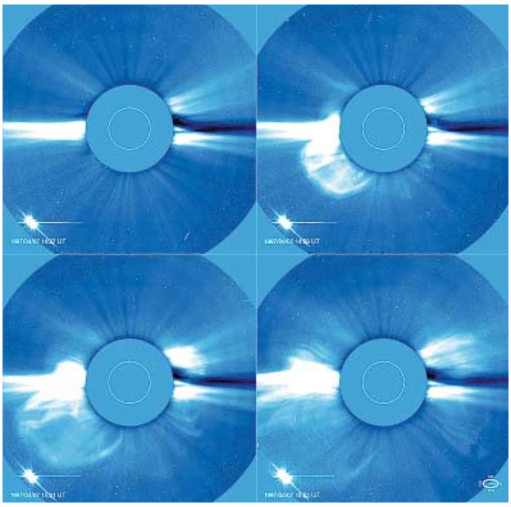

Figure 3. A sequence of images of the coronal mass ejection on April 7th, 1997 taken with LASCO (Large Angle and Spectrometric Coronograph) on board the SOHO spacecraft. The radius of the large circle corresponds to 32 solar radii (approx. 22.4 million km). (http://sohowww.estec.esa.nl/gallery/current/19970407/)

Solar energetic particle events precede CMEs. Particles ejected from the Sun are accelerated to very high energies by interplanetary shocks. The most energetic particles arrive at Earth within tens of minutes after the event on the Sun, penetrate into the Polar Regions to low altitudes and enhance electron density below 100 km.

Magnetic storms are usually the magnetosphere's response to the passage of the coronal mass ejection. During a storm, portions of the solar wind's energy is transferred to the magnetosphere, causing Earth's magnetic field to change rapidly in direction and intensity and energize the particle populations within it. At the same time the electrical currents are enhanced in the ionosphere and induced in the ground.

Associated with magnetic storms are ionospheric disturbances, manifestations of which are changes in the electron density and currents, and the appearance of electron density irregularities with sizes from thousands of kilometres down to centimetres.

The aurora is a light emitted from the polar upper atmosphere as the high-energy electrons bombard it from space. The aurora is probably the oldest known geophysical phenomenon. To an observer, the aurora is an exciting spectacle. Greenish or reddish strips forming draperies, rays and arcs, often stretching over a large portion of the sky, constantly moving and changing, appearing and disappearing. The altitude of the bottom edge of auroral structures is about 100 km. Figure 4 shows one of many woodcuts made by Fritjof Nansen depicting an aurora. In

Figure 4. Aurora - a woodcut by Fridtjof Nansen. (http://www.bellpondbooks.com/aurora4.htm)

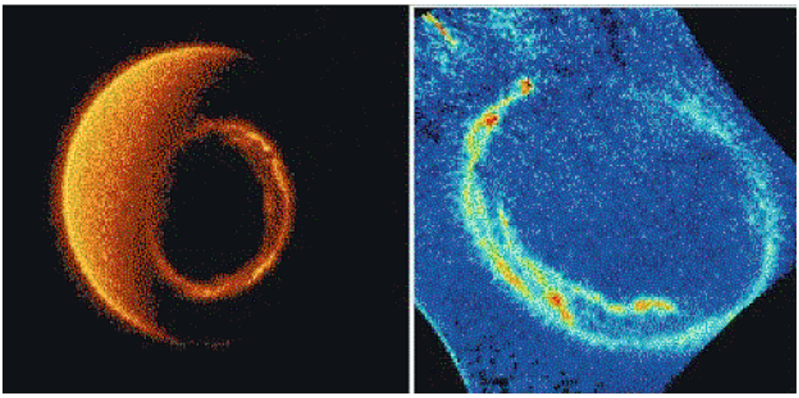

Figure 5. Satellite images of the auroral oval. Left panel: A Dynamics Explorer image from an altitude of 21000 km. The bright crescent is the sunlit dayside.
(http://www-pi.physics.uiowa.edu/sai/gallery/)
Right panel: A Viking image from an altitude of 6000 km taken at ultraviolet wavelengths. The Earth's magnetic pole is in the centre of the ovals.
(http://www.phys.ucalgary.ca/satellites/html/viking.html)

Figure 5 satellite images of aurorae are reproduced. The brightest aurorae form an oval with the magnetic pole at its centre. It expands equatorward during magnetically active periods, when aurorae become brighter and it contracts poleward during magnetically quiet periods.

Practical consequences of space weather

Many of the described phenomena associated with solar activity also have important practical consequences and must be taken into account in the design and operation of technological systems. Figure 6 illustrates some of the effects of solar activity on various systems.

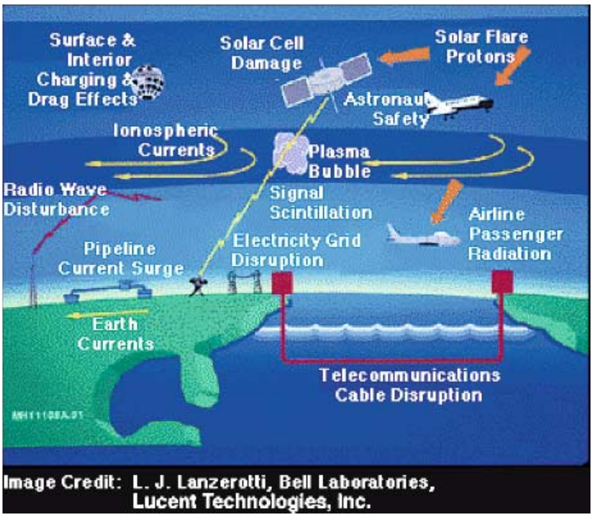

Figure 5. Some of the effects of solar activity on technical systems deployed on the Earth's surface and in space.

Radio communication and navigation

Radio communication links at all frequencies are affected by space weather. Especially sensitive are kHz and MHz links because they rely on wave reflection from the ionosphere. Changes in electron density may cause degradation, or disruption of radio waves propagating within the ionosphere. Ionospheric irregularities may produce signal fading so strong that a signal loss is encountered. Broadband radio noise emitted by strong solar flares may interfere with a wanted signal making its detection impossible. At high latitudes streams of high-energy particles could increase ionization causing enhanced absorption of radio waves and preventing radio communication. Such radio 'blackouts' may last for many hours. Likewise, radio waves at higher frequencies (hundreds of MHz and GHz) that penetrate the ionosphere and are used on satellite radio communication links and navigation systems are affected when solar activity causes sudden variations in the density of the ionosphere. For instance, the Global Positioning System (GPS) uses signals from several satellites to measure the range to the satellites and determine the position of the receiver. Actually the range is determined from the propagation time between the transmitter and the receiver. This propagation time is dependent on the ionosphere electron density and therefore will change with solar activity. Use of dual-frequency GPS receivers can, to some extent, compensate for this effect. However, another ionospheric effect, scintillation or rapid fading of the amplitude and phase of the signal, can not be conquered so easily. Scintillation is caused by electron density irregularities that scatter and diffract radio waves. When the depth of fading exceeds a certain limit, the receiver fails to track the signal and the propagation time can not be measured.

Power systems

Geomagnetic storms can have a devastating and expensive effect on power systems. Currents induced by a variable magnetic field in the long transmission lines cause saturation of the transformer core. Associated increased heat may damage the transformer and release the relays shutting off the power. That is exactly what happened on March 13, 1989 when the whole of Quebec province was left without power for over 9 hours. The net cost of this 'Quebec blackout' was estimated at 13.2 million Canadian dollars. In addition to that, the purchase of replacement power cost about 17 million dollars.

Pipelines

A variable magnetic field can induce currents in long pipelines and surrounding soil. Under normal conditions, to protect against corrosion, the pipelines are equipped with special devices that keep the pipeline at a small negative potential with respect to the soil. During a magnetic storm this potential may increase above the safe value, the pipeline corrosion protection system fails, corrosion attacks the pipeline joints and its lifetime is reduced. In addition to that, possible leaks through the pipeline cracks may constitute a threat to the environment.

Radiation hazards

Normally, the atmosphere and magnetosphere protect us sufficiently well from solar high-energy radiation, but satellite operations, astronauts, and even passengers in commercial jets travelling at high altitudes are subject to elevated dosages of radiation. During severe magnetic storms, occurring on average 3 times per solar cycle, strong radiation affects computer memory chips causing loss of control, solar panels may be degraded, imaging equipment may be subject to noise, tracking instruments can loose orientation. At the same time, astronauts and aircraft passengers are exposed to the radiation equivalent of more than 10 chest x-rays. A primary means of reducing this hazard is to modify the flight path, which requires the ability to predict the occurrence of solar particle events.

Climate

There is increasing interest in the long-term effect of solar activity on climate change. There are well known periods when low sunspot activity was associated with cold climate conditions. The famous example is the Maunder minimum (see Figure 2) when the weather was so cold that ice covered the Baltic Sea.

Recent measurements show that solar irradiance varies over the solar cycle by as much as 0.1%. It is very unlikely that such a small variation produces measurable climate changes. Antropogenic agents are probably of higher importance. However, we can expect that long-term variation, possibly with larger amplitude, could influence the global climate.

Final remarks

Accurate specification and forecasting of space weather may help system operators to take necessary action in advance and will aid in the design of less vulnerable technological systems. For this purpose, special space weather services, similar to the meteorological services, have been formed in many countries. They use large banks of data and sometimes very sophisticated models to provide necessary information to interested services, military and civil. However, one should understand that solar-terrestrial relationships are extremely dynamic and complex, and some requirements established by users are difficult or not possible to meet. As yet!

Acknowledgements

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