Geomagnetic storms. Measurement and forecasting

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1 Introduction – Effects of magnetic storms on technology

”Geomagnetic storms created aurora borealis these weekend as predicted by NASA” could be read in some Swedish newspapers on 16 may 2005. The aurora borealis aroused on 13 may 2005, when a Coronal Mass Ejection (CME) erupted from the Sun. This was directed towards the Earth and was observed by the satellite SOHO (Figure 1). It impact Earth on 15 may and the aurora borealis created could be observed as far south as the northern Africa and the south of Japan.

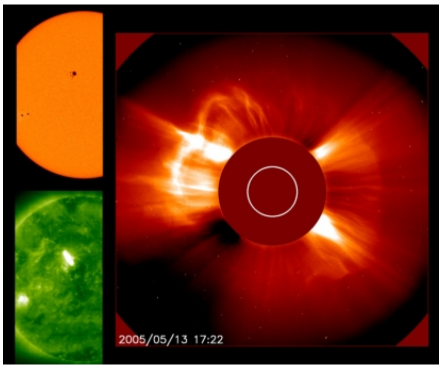

Figure 1. The large sunspot of the active region can be seen in the yellow image of the Sun, at the upper left.
The flare can be seen as a bright, almost white area in the image of the Sun's corona at the lower left.

The observations of aurora borealis, created by geomagnetic substorms, are beautiful, but space weather phenomena, as geomagnetic storms, have a variety of effects on technology. The high energy particles affect satellites while the increased ionization disrupts communication and navigation systems, causing disoperation or even damage. The magnetic disturbances affects operations that use the magnetic field but it could also induce electric currents in power lines and pipelines. One major incident happened on 13 March 1989, at the peak of the 11-year solar activity (sunspot) cycle that began in 1986. The entire Hydro Québec power grid in Canada went down during a geomagnetic storm. It appeared that high currents between grounding points caused protective devices to operate, and transformers to fail. The large direct currents through transformers saturated the cores, and the reduced impedance allowed excessive currents that burned out the transformers. The same storm also made the U.S. Navy’s navigational satellites to be taken out of service for about a week. Some Power grids in Sweden were also affected. Solar storm impacts on electric power systems were first observed in the United States in 1940 but with all new technology it have become of great importance to get more knowledge about it.

2 What is a (geo)magnetic storm?

A (geo)magnetic storm is a temporary disturbance of the Earth’s magnetosphere. In one respect the solar storms themselves shield the Earth. They reduce the intensity of cosmic rays, energetic particles reaching the Earth from the Galaxy. There is two basic causes. The first is when the Sun emits a strong surge of solar wind called a coronal mass ejection (CME). When this strikes the Earth’s magnetiosphere it create a disturbance in the field, creating electric currents in the near-Earth space environment, which, in turn, generate additional magnetic-field variations. This often marks the start of a storm and is called a “storm sudden commencement (SSC)”. The continuing interaction between the solar wind and the magnetosphere increases the number of charged particles. These particles drift around the Earth creating a ring current that produces a depression of the horizontal magnetic field (the “main phase”). This is followed by the "recovery phase", lasting one day or more, during which the ring current decrease and the magnetic field returns to normal. This type of storms is usually the strongest and strikes the Earth's magnetic field 24 to 36 hours after the event. These fluctuations may cause satellites getting outside the Earths protecting magnetic shield, and become more exposed to damaging particles.

The second is when the Sun's interplanetary magnetic field is linked together with Earth's (Figure 2). In the complicated flow of the solar wind, the interplanetary magnetic field can take on virtually any orientation. Sometimes it assumes a southward, and make the orientation of the interplanetary magnetic field to be opposite of the orientation of the Earth's magnetic field at the magnetopause. This can make the magnetic fields to be linked together. It is not common but when it occurs, charged particles from the Sun, that otherwise would be deflected by the Earth, can easily enter the magnetosphere and create highly strong currents. These currents generate a magnetic field that counteract with Earths magnetic field and we get a geomagnetic storm. As a result of the interaction with the solar wind, the magnetosphere is compressed on the dayside and an extended magnetotail is formed on the nightside. Occasionally, the field in the tail can reconnect in an explosive manner producing a so called geomagnetic substorm. The charged particles can then penetrate into the upper layers of the atmosphere along the originated open field lines, where they can create aurora borealis.

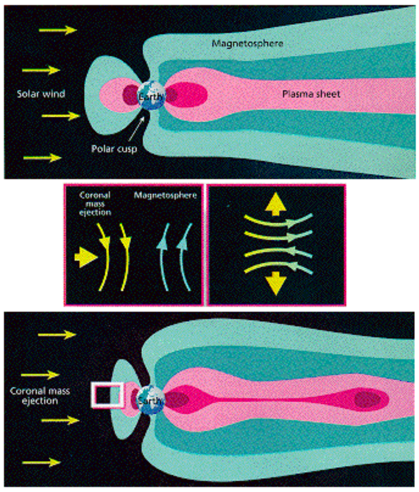

Figure 2. The Sun's magnetic field interact with Earth's, compressing the magnetotail on the nightside.

3 Forecasting of magnetic storms

How can magnetic storms be forecasted? Some eruptions on the Sun is known to cause magnetic storms. These eruptions often send out light, radio waves or X-rays which travel to Earth in about 8 minutes. The electrically charged particles who is the actual cause of magnetic storms, however, take a few days to reach Earth. By using instruments to watch the Sun, the intervening space and the Earth´s magnetic field, magnetic storms can be detected before they reach the Earth. But the theories used are far from perfect.

The data used to forecast magnetic storms are first of all coming from the satellites watching the Sun. These data can tell about the Sun's features such as active regions, coronal holes and eruptions as solar flares and CME. The ACE (Advanced Composition Explorer) satellite, for example, tells about the conditions in the solar wind and the streams of particles coming from Sun. There is also data from different magnometer recording sites around the world telling what the effects on the Earth magnetic fields are due to the Sun's activity. By looking at patterns and data together with theories scientist can forecast what they expect the Earth's magnetic field will behave in the near future. These daily or even time-updated reports can be found on the internet for companies that know that there equipment can be endangered during a magnetic storm.

4 Measuring by satellites

A multinational space fleet (ISTP, the International Solar-Terrestrial Physics Programme) is busy making better sense of the Sun's behaviour and its effects on the Earth. Six of these spacecrafts have been built in Europe. These are SOHO (1995), which is a multi-purpose satellite observing the Sun, Ulysses (1990) flying over the poles of the Sun and Cluster (2000) with four identical satellites that will study the planet's magnetic field and electric surroundings in 3D, specially the effects of the solar wind, which buffets Earth's protective magnetosphere.

The *L1 liberation point* is a point of Earth-Sun gravitational equilibrium about 1.5 million km from Earth and 148.5 million km from the Sun. The *L1 liberation point* provides a very useful position for monitoring the solar wind before it reaches Earth and for other purposes. Currently two satellites are stationed near L1 - ACE (Advanced Composition Explorer) and SOHO (Solar and Heliospheric Observatory).

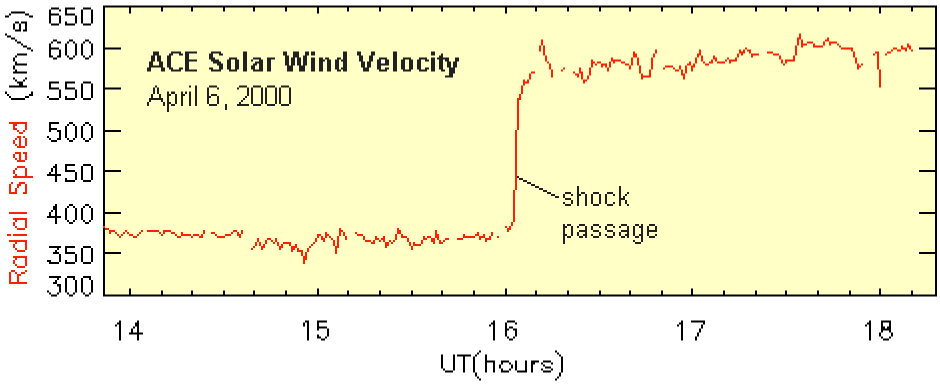

Figure 3. Data from ACE, on April 4, 2000, showing an interplanetary shock wave caused by a solar CME.

The ACE (1997) is carrying six high-resolution sensors and three monitoring instruments samples low-energy particles of solar origin and high-energy galactic particles. ACE can measure solar winds with high reliability and events detected reach Earth about an hour later. Figure 3 pictures data from ACE on April 4, 2000, showing the speed of the solar wind measured at the L1 liberation point. Where the wind velocity jumps from 375 km/s to nearly 600km/s marks the passage of an interplanetary shock wave caused by a solar coronal mass ejection (CME). The material in the shock front left the Sun two days earlier.

At the same time as ACE registered the shock wave, the SOHO captured pictures of a full halo coronal mass ejection (Figure 4). The solid circle in the middle is blocking out the intense light of the Sun so that the corona becomes visible. The halo in the picture is special because the CME is moving directly toward Earth and create an almost perfect halo around the Sun.

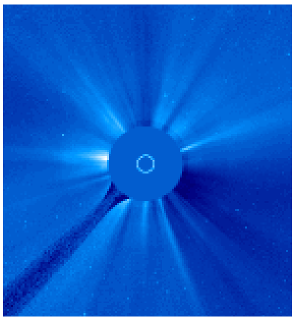

Figure 4. Picture taken by SOHO on April 4, 2000, showing a full halo CME.

5 Ground based measurements

The magnetic field can also be measured from ground based magnetic observatories around the world, by either liquid or vapour magnetometers. To get an identical comparison geomagnetic properties are used to indicate the severity of disturbances in near-Earth space. The most common indices used are Kp and Dst. To determine these, data is used both from the ground based measurements and data coming from the ACE. Models can make short-term forecast of these two indices.

5.1 The Disturbance Storm Time index (DST)

Similarly to Earthquakes and the Richter scale, scientists have defined an index to estimate the severity of geomagnetic storms - the Disturbance Storm Time index (DST). It is obtained from magnetometer stations near the equator. At such latitudes the northward component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current.

During a magnetic storm, the magnetic field measured at the Earth's surface weakens and DST is a direct measure of the hourly average of this perturbation. The more negative, the more intense is the storm. By definition, a magnetic storm occurs when the DST index exceeds -100 nT. Figure 5 shows a plot for the DST index for May 2005 taken by Cluster. Two moderate (~ -100 nT) magnetic storms occurred, one on 8 May and one on 30 May. A more abrupt and intense storm happened on 15 May with a DST index of ~ -250 nT in a couple of hours.

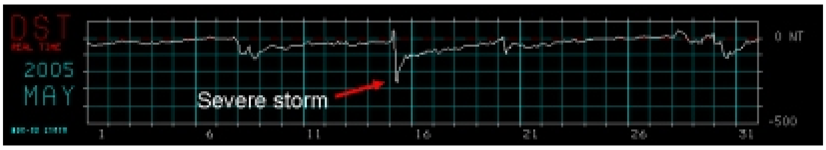

Figure 5. Plot of the DST index for May 2005, taken from Cluster.

5.2 The Ap and Kp index

The Ap and Kp indices are a measurement of the behaviour of the magnetic field in and around the Earth. The difference between them is that Kp is a logarithmic change in the Earths magnetic field while Ap is linear.

The **Kp index** is obtained from a number of magnetometer stations at mid-latitudes. It measures the geomagnetic fluctuations and uses a scale from 0 to 9 depending on the strength of the fluctuations in the last three-hour period. 0 means fluctuations below 5 nT and 9 over 500 nT. The larger the value of Kp, the further south the aurora can be seen. The name Kp originates from “planetarische Kennziffer” (= planetary index).

The **Ap index** is a daily value on a scale from 0 to 400 to express the range of disturbance of the geomagnetic field. It is obtained by converting and averaging the eight, 3-hour Kp index values.

5.3 Geomagnetic storm levels

Geomagnetic storm levels are determined by the estimated 3-hourly planetary Kp-indices. They are numbered G1-G5 where G1 is a minor (Kp=5) and G5 an extreme (Kp=9) disturbance. Solar and radio disturbances have similar indices, S1-S5 and R1-R5.

The magnetic storm on April 4, 2000 (Figure 3 and 4) reached the level G4.

6 Summery

Today it is of great importance turning off equipment that is sensitive for changes in the magnetic field. But it is also difficult. The increased radiation from an eruption from the Sun can be seen after 8 minutes, but it doesn’t mean that there have been a CME. A CME can only be noticed by the ACE-satellite, placed between the Sun and Earth. From the ACE it will take one hour before the Solar wind reach Earth, or even less if it is a storm where the particles travel with a much higher velocity. The north-south component of the Solar winds magnetic field can change and also the velocity while it coming toward Earth. Thus it is a balance between the time and reliability to make good premonitions.

By using SOHO they try forecasting eruptions and CME’s on Sun before it take place. With the pictures from SOHO and the condition of the solar wind, different models are used to predict geomagnetic storms. The disadvantage is that the models usually aren’t good enough and more research is necessary to improve the understanding and theory behind the phenomena’s.

7 References

Boberg Fredrik. (2003). *Space Weather - Solar magnetic variation and its impact on Earth's atmosphere*, Lunds Universitet

Rönnmark, Kjell (2003). *Lecture Notes on Space Physics. From the Sun to the Aurora*, Umeå universitet.

ESA Science and Technology (2006-10-16)
(*http://sci.esa.int/science-e/www/area/index.cfm?fareaid=1*)

Geological Survey of Canada (2006-10-16)
(*http://www.spaceweather.gc.ca/index_e.php*)

National weather service – Space environment centre (2006-10-16)
(*http://www.sec.noaa.gov/Data/info/WWVdoc.html*)

Science NASA (2006-10-16)
(*http://science.nasa.gov/headlines/y2000/ast07apr_2m.htm*)

Max Planck Institute for Extraterrestrial Physics (2006-10-16)
(*http://www.mpe-garching.mpg.de/projects.html*)

Wikipidia – the free encyclopaedia (2006-10-16)
(*http://en.wikipedia.org/wiki/Geomagnetic_storm*)

USGS – National Geomagnetism Program (2006-10-17)
(*http://geomag.usgs.gov/intro.php*)

Space Physics Text Book of Oulu (2006-10-17)
(*http://www.oulu.fi/~spaceweb/textbook/storms.html*)

Tony Smith's home page (2006-10-17)
Picture
(*http://www.valdostamuseum.org/hamsmith/13Mar89.html#CME*)