National Aeronautics and
Space Administration

Educational Product	
Educators & Students	Grades 7-12

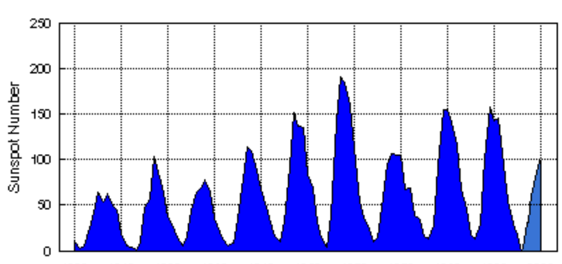
Educational Brief

Are You Ready for Solar Max?

For thousands of years, the Northern Lights' have lit up the skies, and human imagination, with their ghostly incandescence. More often seen in arctic regions, but occasionally as far south as Arizona and Florida, they have inspired both good and ill omen, and a fair measure of misunderstanding. What has changed in the last 150 years or so is that our steady technological advances have finally made it possible for us to see how solar storms are produced, and how their effects make it all the way to the Earth!

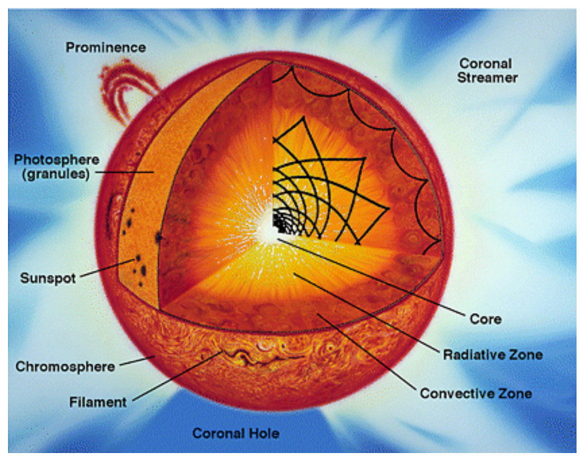
Solar Storms

The sunspot cycle marks out changing episodes of storminess and quiescence. During sunspot maximum conditions, many sunspots dot the Sun's disk and this is a time when major solar storms can be spawned. About 5 years later, few spots can be seen and the Sun is relatively calm, although from time to time it can still produce a sizable storm. The interval between sunspot maxima is about 11 years. 93 million miles away, many different systems in the Earth seem to beat in step with this subtle, solar rhythm. These distant solar storms can also create episodes of extremely bad 'space weather'. What is the source of all this solar unrest?



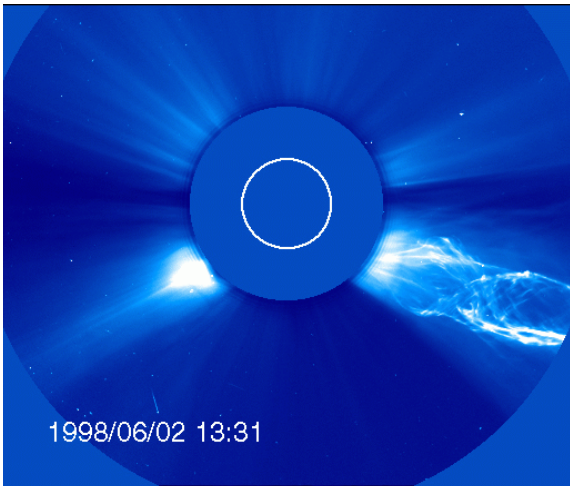
Sunspot cycles during the 20th Century.

The Sun is an active star. Inside the Sun, atoms are shorn of their electrons at temperatures of hundreds of thousands of degrees to form the Fourth State of Matter: Plasma. These plasmas boil like oatmeal in a pot, heated by the 15 million degree nuclear hot plate deep in the Sun's core. The convection currents take up nearly 1/3 of the outer layers of the Sun, and it is somewhere in this turbulent caldron that rivers of charged particles generate powerful magnetic fields.



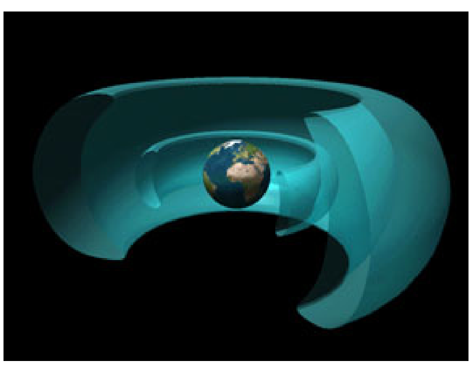
The solar magnetic field is carried by convection currents to the surface where it gets concentrated into the dark spots we see as sunspots. Over time, these sunspot fields can merge together and sometimes short circuit. Like a skillful seamstress, the Sun breaks these magnetic field loops and re-ties them into larger and larger magnetic shapes nearly as large as the Sun itself.

When magnetic fields short circuit, powerful solar flares hurl protons and electrons to near-light speed, sending blasts of X-rays into space. Millions of miles away, the electromagnetic and particle radiations from these flares can strike the Earth and disrupt radio and satellite communication. The Sun's corona can also spawn billion-ton clouds of plasma. Traveling at over a million miles per hour, some arrive at the Earth in only a few days; solar scientists call these events coronal mass ejections (CMEs).



CME event seen by SOHO: an ESA/NASA satellite.

In many ways, they are actually more noxious than the more popularly known solar flares. CMEs pummel the magnetic field of the Earth like a million mile-wide sledgehammer, and upset its delicate balances of trapped particles in the van Allen radiation belts and elsewhere in the Earth's environment.

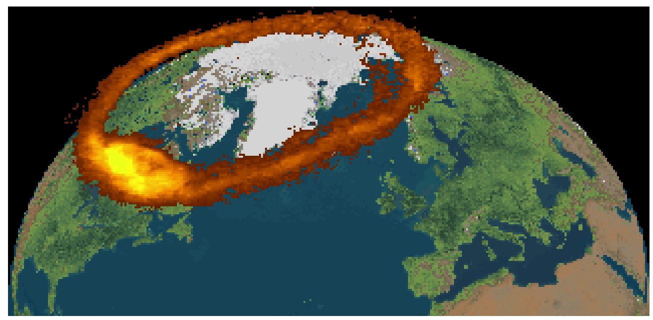


The van Allen radiation belts were discovered during the early years of the Space Age. Shaped like donuts with the Earth at the center, they are a hazard to satellites and astronauts because of their energetic particles.

To the naked eye, the first hint that space weather conditions have taken a turn for the worst is usually a spectacular aurora borealis (called 'Northern Lights' in the arctic regions of the Earth), and an aurora australis (called 'Southern Lights' in the Antarctic regions). Like a miner's canary, they signal invisible but powerful forces at work.

The Northern Lights

Aurora are produced by currents of charged particles, mostly electrons and protons, that flow along the Earth's gossamer-thin magnetic field. They enter the thickening atmosphere over 500 miles above our heads, and collide with atoms of oxygen and nitrogen. The atoms give off dazzeling hues of red, green and blue, painting the skies in delicate curtains of light. Just as electricity in a copper wire can produce a magnetic field, these celestial currents temporarily change the Earth's magnetic field and cause 'magnetic storms'. From the ground, compass needles suddenly dance in erratic directions for hours until the storm passes.

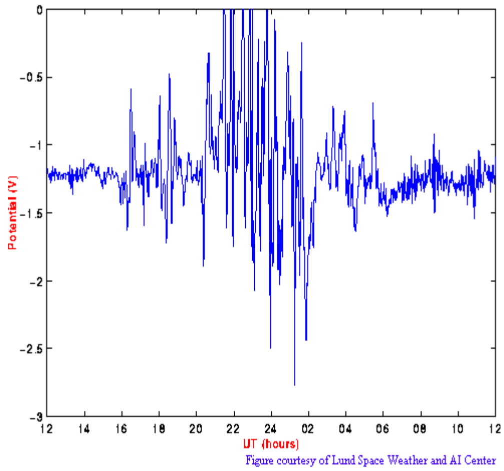


As seen from a satellite, the aurora borealis looks like a fiery ring of light called the 'auroral oval'. A similar ring can be seen in the polar regions of Jupiter and Saturn with the Hubble Space Telescope.

Whenever aurora have marched across the night time skies the world-over, they have also produced electrical and radio interference here on the ground.

Hello? Can you hear me?

By the late 1800s, vast networks of wires were strung-up across many of the continents to carry telegraph and telephone traffic. The stage was set for one of the largest physics experiments in history. The English physicist Michael Faraday had already discovered in his lab that if you took a magnet and ran it by a loop of wire, electrical current would start to flow in the wire. Faraday's 'magnetic induction' discovery was soon put to use in creating the first electric generator. By this time, nature also had its way with the thousands of miles of telegraph wires strung-up on trees and poles across North America. Electrical currents induced by the changing fields during magnetic storms were often so powerful that telegraphers didn't need battery power to send their dits and dahs down the line; auroral currents were more than enough to do the work by themselves.



Voltage changes on a section of electrical cable during the time of a magnetic storm on November 8-9, 1991.

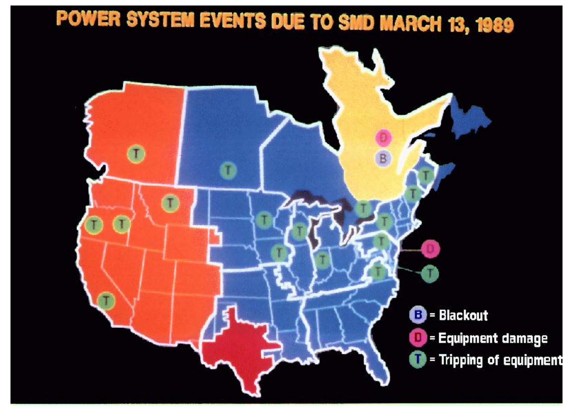
Some operators were even treated to near-electrocution! It made no difference if these wires were under the ocean. In the Atlantic Cable between Scotland and Newfoundland, 2,600 volt surges were recorded during the March 1940 magnetic storm.

Our Vulnerable Technology

In the last century, telegraph wires were directly affected by magnetic storms. Today, we find ourselves less aware of these technological impacts than our grandparents were, or even our parents. Against the distracting glow of city lights, few people have ever seen an aurora. Fewer still have ever experienced a blackout caused by one.

During this century, short-wave broadcasts would be blocked for hours, and then resume their normal clarity as a solar flare waxed and waned on the distant Sun. Although these kinds of problems cleared up in a few hours, other effects were more long lasting and a lot more expensive to deal with. A 230,000 volt transformer at the British Columbia Hydroelectric Authority blew up during the August 2, 1972 storm. Quebec was plunged into a full-scale power blackout during the March 13, 1989 storm affecting over 6 million people for nine hours.

According to John Kappenman, an electrical engineer at MetaTech Corporation, transformer failures happen more often in regions where magnetic storms and aurora are common, such as the Northeastern United States and Canada.

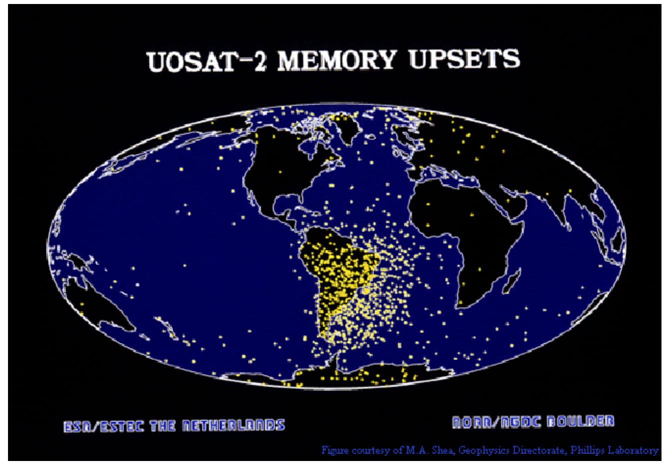


A map of North America showing the various electrical service problems recorded during the March 13, 1989 Great Aurora.

These failures cause $100 million in equipment damage each sunspot cycle. Engineers have also seen how the numbers of these failures even follow the sunspot cycle. By some estimates, a U.S. blackout similar to the 1989 Quebec event causes as much economic damage as the multi-billion dollar Hurricane Floyd. With fewer power plants being built, and increasing demands for electricity, there is less reserve power to help us ride out solar storms today than there was ten years ago.

Long uninterrupted pipelines are just as good as telegraph and power lines for bringing solar storms 'down to Earth'. Geomagnetic currents flowing in pipelines are known to enhance the rate of corrosion over time, and this can have severe cumulative effects. The Alaskan oil pipeline, for example, was built during the mid-1970s, and specifically designed to reduce these currents by using short lengths of pipe. In Finland, the entire national pipeline system is constantly monitored for these corrosive, geomagnetic currents. Pipeline corrosion, when unchecked, can lead to costly supply interruptions and even catastrophic ruptures as the pipeline walls become weakened.

Despite careful designing to avoid the worst of these currents, the Alaskan oil pipeline will have a shorter life expectancy because of corrosive currents produced by sudden geomagnetic storms.



Memory upsets in the UOSAT-2 satellite as it orbited the Earth. The cluster of upsets over South America coincides with a region where the van Allen Radiation Belt is closest to the Earth in the satellite's orbit, also called the South Atlantic Anomaly.

Today's world is a lot different than it was just 10 years ago. In recent years, hundreds of millions of subscribers have begun to expect satellite pager and communications technology to run flawlessly. We rely on uninterrupted power supplies to run our computer-rich, internet-laced, civilization. Hundreds of billions of dollars of satellites now orbit the Earth. Astronauts are also spending much more time in space than they did during the last solar cycle. All of these enterprises are at risk for damage by solar storms.

Satellite Problems

One of the first discoveries made in the early years of the Space Age was that space is 'radioactive'. Up above the protecting layers of the atmosphere, high-energy particles from the Sun, the Earth's own magnetic field, and even deep space, all come together and bathe any unshielded object in potentially hazardous dosages of radiation.

The most destructive ingredient for satellites seems to be the high-energy electrons which do their damage by penetrating deep into a spacecraft and affecting delicate electronics. Computer bits can suddenly change from '1' to '0' with tremendous consequences for the way a satellite functions if the bits are in some crucial memory locations, or in the commands a satellite executes.

The list of major satellites that have been incapacitated by adverse space weather is a long and costly one. For example, Marecs-B, a marine navigational satellite, was disabled during a week of intense auroral activity in February 1982. ANIK E-1 and E-2, two Canadian communications satellites, were disabled in January 1994 because of the elevated activity of high-energy electrons in the Earth's magnetic field. On January 11, 1997 AT&T experienced a massive power failure in its Telstar 401 satellite within hours after a solar storm arrived at the Earth.

There are thousands of working satellites in space. Why is it that a specific storm only seems to affect a few of them, if any at all? Like a tornado entering a Kansas trailer park, they seem to affect some satellites, while leaving their next-door neighbors seemingly unscathed...or do they?

A major problem in tracking down cause-and-effect is the lack of satellite data available to scientists. Most satellites are owned by either the military or by the commercial satellite sectors. These groups have no interest in making public their vulnerabilities to solar storms. Billions of dollars of commercial satellite profit can ride on whether investors see a satellite resource as a naturally risky venture or not.

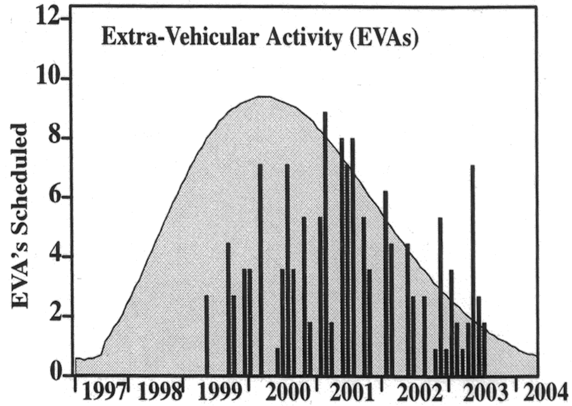
Satellite insurance companies can also be forced to pay out millions of dollars on risky satellite designs that can be affected by space weather events. In 1998, satellite insurance companies paid out $1.8 billion in claims; half of which was for satellite failures in orbit.

Solar activity doesn't have to take a direct swipe at a satellite to do it harm. During solar storms, the Earth's atmosphere expands by hundreds of miles. This increased atmospheric friction causes satellite orbits to change. The premature demise of such satellites as the Solar Maximum Mission (April 1990) and Skylab (July 1979) is the result. To avoid a similar fate, even the International Space Station will have to be re-boosted each year. During the Quebec blackout, U.S. Space Command had to re-compute the orbits for over 1,300 objects affected by the increased air resistance. Satellites placed in Low Earth Orbit (LEO) only a few hundred miles above the surface of the Earth are still inside the Earth's atmosphere. Solar maximum conditions can greatly shorten their lifetimes which are usually less than 10 years. Despite the known risks of putting expensive satellites in low Earth orbits, 'LEOs' are still considered prime orbital real estate for the newest generations of communication satellite networks.

"That was then...this is now"

Between 1997 and 2007 as many as 1000 new satellites will be launched, and most of these will be placed into LEOs. Some investment companies are calling the 21st century satellite industry a major gold mine for spectacular stock growth. Services that rely on satellites could reach a staggering $80 billion. To meet this demand, many companies are launching networks containing dozens and even hundreds of satellites.

There are also human health risks that go along with solar storm conditions. Astronaut Shannon Lucid reported that on the MIR Space Station, the typical radiation dosage was equal to about eight chest X-rays each day. During a solar storm in 1990, MIR cosmonauts received a full year's dosage in a matter of a few days. The main construction work for



The schedule of EVAs by International Space Station astronauts compared with the predicted rise of solar sunspot cycle 23.

the International Space Station will occur between 2000 and 2002 just after the peak of the current sunspot cycle. For health reasons, astronauts are not permitted radiation dosages higher than 600 rem each year, or 50 rem during any single year. The radiation that an unexpected, large solar flare can provide a space suited astronaut can equal or surpass this amount. Fortunately, space weather forecasters have developed methods for reliably detecting these exceptional, but rare, flares before they become a problem to astronauts.

Meanwhile, the Federal Aviation Administration is looking into some way of providing radiation hazard alerts to flight crews, and especially to pregnant stewardesses. In Europe, their civil aviation agency already has these safeguards in place.

Preparing for the Worst

The next solar cycle (Cycle 23) is already here, and if the blackouts, communication outages and satellite problems of the last few cycles are any hint of things to come, we should expect more examples of these kinds of impacts.

The good news is that more people are becoming aware of the need for paying attention to solar storm effects. Electric power companies have begun to hire space weather forecasters, and use advanced warning of inclement space weather conditions to safeguard the power grid. No one wants a repeat of the Quebec blackout! Unlike ice storms which cause

PJM Public Service Step Up Transformer

Severe internal damage caused by the space storm of 13 March, 1989.

blackouts too, solar storms burn out million-dollar transformers which are more difficult to replace on short notice.

Satellite manufacturers, however, have a different choice to make. They can either use more radiation shielding, or use less sophisticated technology and provide fewer services for the customer. Shielding is dead weight, but it costs just as much per pound as sophisticated electronics to put into space. Most of the time, engineers have no choice but to use commercial off-the-shelf electronics because there are no 'rad-hard' versions of the most high-end electronic components they need. Electing to build light-weight satellites with off-the-shelf electronics makes satellites more vulnerable to solar storm effects. One solution to this dilema is to be more careful in how you design a satellite, and try to predict just what will happen when a solar storm arrives.

Space Weather Forecasting

In the mid-1960s, NASA became a leader in developing and refining models of the Earth's space environment. But, these 30-year-old models do not include solar flare events, which can produce a year's worth of radiation damage in a few days or less. Since the mid-1980's, NASA has invested billions of dollars in research satellites such as SOHO, POLAR, and IMAGE among many others. Newer generations of models that will be much more accurate than the older models are now being developed, but they are not ready yet. So satellite engineers have to rely on a patchwork of older models to design their satellites.

In 2000 we are at the peak of the current solar cycle. At risk will be hundreds of satellites in LEO networks destined to carry an increasing cargo of critical information from ATM transactions and Internet traffic, to telephone and pager messaging, and all insured for billions of dollars.

Unlike the short-wave interruptions and telephone interference of the past which we tolerated in the earlier decades of the 20th century, there will probably be no backups to take over for the affected satellites. As new demands make satellites and uninterrupted power a vital necessity to our society, we may just have to get used to 'space weather' impacts which most of us have never experienced before.

Resources

The NASA, Office of Space Science's Sun-Earth Connection Education Forum (SECEF) at

http://sunearth.gsfc.nasa.gov
or
http://sunearth.ssl.berkeley.edu

provides a one-stop resource area for education products developed by all of the NASA satellite missions that perform solar-terrestrial research.

At SECEF, teachers will find links to exemplary classroom activities, and a catalog of NASA products such as posters, brochures and introductory primers on space physics and solar science.

The SECEF web site provides links to 'Ask an Expert' services where students, teachers and the general public may read thousands of posted questions and answers about specific topics in astronomy provided by many different sun-earth missions.

You can also use the SECEF web site to visit the home pages of all of the NASA missions which are working at the frontiers of science to understand how the Sun affects the Earth.

Questions about the Essay

1) What do scientists mean by the term 'space weather'?
2) Compare space weather to ordinary earth weather. How are they similar? How are they different?
3) Can you describe three ways in which space weather affects our technology?
4) What kind of space weather hazard will International Space Station astronauts have to worry about?
5) How is a major space weather event sometimes like a tornado?
6) Is it practical to provide satellites with all the shielding they need to protect them from space weather events?
7) If you were taking a trip to Mars, what kinds of hazards would you have to worry about?

Classroom Activity :

The student will construct a graph of the number of sunspots. The student will explore patterns in the data, and locate the maxima and minima of the sunspot cycle.

1) Divide the students into groups and assign a time period from the data table that each group will graph. Some possible lengths are the 1900s, 1800s; every 50 years; a column of the table (be aware that assigning less than 50 data points will prevent pattern recognition).

2) Students will then construct the graph of the table on graph paper. Some possible options here are to have students each construct the graph, have each group use their assigned data and put the results of the class as a whole on the wall, or have the groups do a graph of the entire data. Be sure to agree upon a consistent scale for ease of construction and display.

3) Discuss the results of the entire sunspot table as a whole. Look for patterns such as maximum and minimum. How often do the cycles happen? Is it a regular cycle? What is the average number of years between cycles? What are the longest and the shortest cycles in the series? If you compared the shapes of each cycle, are the curves the same shape on each side of the maximum point? How do the shapes correlate with the maximum spot numbers that were reached?

5) Students predict when the next maximum will occur near 2000. Students will then construct what the graph would look like if this pattern continued on through the year 2099. Have the students compare their predicted curves for the 21st Century and explain how they made their predictions.

Average yearly sunspot counts 1700:1998

Year...N	Year...N	Year..N	Year..N	Year....N
1700...5	1760..63	1820..16	1880..32	1940..68
1702..16	1762..61	1822..4	1882..60	1942..31
1704..36	1764..36	1824..9	1884..64	1944..10
1706..29	1766..11	1826..36	1886..25	1946..93
1708..10	1768..70	1828..64	1888..7	1948..136
1710...3	1770..101	1830..71	1890..7	1950..84
1712...0	1772..67	1832..28	1892..73	1952..31
1714..11	1774...31	1834..13	1894..78	1954..4
1716..47	1776..20	1836..121	1896..42	1956..142
1718..60	1778..154	1838..103	1898..27	1958..185
1720..28	1780..85	1840..65	1900..9	1960..112
1722..22	1782..38	1842..24	1902..5	1962..38
1724..21	1784..10	1844..15	1904..42	1964..10
1726..78	1786..83	1846..61	1906..54	1966..47
1728..103	1788..131	1848..125	1908..48	1968..106
1730..47	1790..90	1850..67	1910..19	1970..104
1732..11	1792..60	1852..54	1912..4	1972..69
1734..16	1794..41	1854..20	1914..10	1974..34
1736..70	1796..16	1856..4	1916..57	1976..13
1738..111	1798..4	1858..59	1918..81	1978..92
1740..73	1800..14	1860..96	1920..38	1980..154
1742..20	1802..45	1862..59	1922..14	1982..116
1744...5	1804..48	1864..47	1924..17	1984..46
1746..22	1806..28	1866..16	1926..64	1986..14
1748..60	1808..8	1868..38	1928..78	1988..98
1749..81	1809..3	1869..74	1929..65	1989..154
1750..83	1810..0	1870..139	1930..36	1990..146
1752..48	1812..5	1872..102	1932..11	1992..94
1754..12	1814..14	1874..45	1934..9	1994..30
1756..10	1816..46	1876..11	1936..80	1996..11
1758..48	1818..30	1878...3	1938..110	1998..38