Background Information

Solar Storms? Why Should I Care?

A Historical Perspective by Dr. Sten Odenwald

"Telephone and telegraph networks failed and equipment burst into flame…a plane crashes killing 18 people…a bustling city loses power trapping thousands of people inside elevators…satellites malfunction and in an instant millions of people lose touch with critical services, doctors and children."

These are not the theatrical elements of some low-grade science fiction movie, they are just a few of the many similar events that played out during severe solar storms of the past century.

Solar storms have always caused spectacular auroras to take the skies, dazzling and humbling all who were fortunate to be in the right geographic locales at the right times. Today, these storms pass by with far more consequence – costly lessons that our technology is still not immune from an ages-old phenomenon.

Long Before Cell Phones

The Sun's constancy as a source of light and heat has been celebrated for millennia, and even deified by many civilizations. Yet this constancy hides a more fickle personality, whose cyclical tantrums of quiescence and storminess has only been recognized 'yesterday' in terms of the great pageant of human history. Before the sunspot cycle was discovered in the mid-1800s, sunspots were a surprising feature of the Sun, but there was little practical benefit to this knowledge. Did their comings and goings have something to do with the weather? The connection between the lovely northern lights and the everyday world was also rather tenuous. Were they really messages from 'beyond' alerting us to some hopeful, or foreboding, event about to happen?

Auroras had held their secrets very tightly for all these centuries. Careful observers soon paid attention to them as astronomical events rather than just some random atmospheric will-o-the-wisp. It didn't take long to recognize that auroras were more common in the northern skies when sunspots dotted the solar surface. Compasses would go haywire whenever a strong aurora peeked its glowing face over the horizon. Still, even with these tantalizing clues, the exact relationship between these dramatically-timed solar and terrestrial phenomena was largely a matter of high-brow conjecture.

At the end of the day, why should anyone on the street care about the appearance of auroras other than their being, for some, an uncommon natural light show to break up the evening rituals after a long day at work?

The Sun-Earth Connection Discovered

This apathetic state of affairs ended on September 2, 1859. In England, the wealthy amateur astronomer Richard Carrington observed a rare but spectacular flare near a large sunspot. Within 17 hours, a domino-fall of invisible events was set into motion, spawning major aurora sightings all around the world. Telegraph disruptions also sprang up everywhere as powerful electrical currents beneath the ground found their way into the high-tech circuitry, bursting some into flame. Among the many newspaper accounts, we hear of Fredrick Royce at a Washington, D.C telegraph office who was nearly electrocuted by these currents while sending a routine message on behalf of a rather impatient client. Over 200 reports filled the pages of the scientific journals and newspapers of the day, reinforcing the perception among scientists and the general public that solar activity could occasionally spawn some very nasty consequences.

Although it was the biggest solar storm in the last 150 years, its technological impact was actually pretty minor. In the tabulation of solar storm disturbances and how they can affect us, timing is everything. In 1859, human society was rather far removed from the kinds of technologies and day-to-day behaviors that connect directly to the Sun's tantrums.

The world-wide telegraph disruptions of 1859 were eventually followed by lesser storms that spawned in their wake, causing progressively more disturbing telegraph disruptions in 1872 and 1882. By the 1890s, the ascendancy of telephone networks and operator-assisted exchanges only transferred these solar storm impacts to another medium. Ground currents created by solar storms found their way into both telegraphic and telephonic systems with nearly equal ease. The advent of Marconi's 'ether' radio introduced us to a new medium for communication, but this only began a whole new round of solar storm impacts, made obvious by the radio disruptions of 1903, 1907 and 1909 during the infancy of the Radio Age. And of course, the impacts on older technologies did not come to an end with the deployment of the newer ones. In fact, by the 1930s solar storms were rattling the cages of all three communications technologies, telegraph, telephone and radio, at the same time! Literally millions of messages, carrying the commerce and private letters of half a world, were held hostage to the fickle ravages of the mysterious solar storms.

This Means War!

As radio technology evolved to utilize shorter wavelengths in the 1930s, hours-long radio blackouts continued to dog even the most advanced radio technology: a technology that was helpless to overcome these persistent solar effects. There seemed to be no escaping these earthly problems, which frequently made front-page headlines in the major newspapers. This spurred on military and civilian efforts to understand the solar-terrestrial connection so that we could at least attempt to predict when these communication outages might happen. The scientists paid attention to 50 years of historical anecdotes and searched the Sun for angry-looking sunspots. They eventually kept round-the-clock watch on the Sun during June 6, 1944, alerting the Allies to flares that could disrupt vital short-wave messages for the most complex military engagement in history: D-Day.

At this point, solar storms were the big news of the day whenever they happened, though no one could predict exactly when. At the height of the interest in solar storms in 1941, the *Boston Globe* sported a front page banner headline 'U.S Hit by Magnetic Storm' in 2-inch letters, previously reserved for announcing major battles during World War II.

We read in yellowed copies of *The New York Times* about the massive rescue mission in 1957 undertaken in the North Sea for the British submarine Acheron. It was presumed lost after failing to radio-in at the planned time - a message intercepted by a raging solar storm instead. After a hundred reports since 1859 of communications problems, fires and social panic, it was inevitable that a solar storm would be credited with taking a human life. This opportunity happened in 1946.

On September 18, 1946 the Belgian Sabena Airways four engine DC-4 aircraft with forty-four persons on board crossed the Atlantic and was scheduled to land at Gander Airport in northeast Newfoundland. About 22 miles southwest of the airport it crashed, taking the lives of 27 passengers.

Why did the crash happen? For centuries, it was well known that aurora could accompany magnetic changes in compasses by up to tens of degrees. Not a serious problem for the leisurely pace of maritime navigation, but at the speed of a modern aircraft, unexpected bearing changes are hazardous, especially when descending through a thick fog. No one can say exactly what the pilot might have been thinking while solar activity played havoc with the flight compass. Descending through the fog bank on what should have been the last minutes on a safe bearing, the plane found itself at treetop level and collided with a thick stand of pines. At 200 mph, death came in less than a second. The Minister of Budget in Brussels announced soon afterwards that the main cause of the crash was fog and the aurora borealis, whose fading beauty could be seen in the skies over the crash site.

Into the Space Age and 21st Century Communications

As we entered the Space Age and the turn of the 21st Century, the impact of solar storms on our way of life gradually increased until . . .

On March 13, 1989 a massive solar storm caused an electrical power blackout in Quebec that eliminated light and heat for 3 million people, created a major political firestorm, interrupted critical medical operations, and led to charges of incompetence in the Quebec power industry. The same event may have triggered irregular sensor readings during the launch of the Space Shuttle. The Quebec Blackout was THE major and to scientists almost legendary textbook example of how solar storms can cause obvious problems.

As of this writing, many space physicists have expressed amazement in our good fortune that no electrical blackouts have since occurred on the scale of the Quebec March 13, 1989 event. There was a minor electrical blackout in Sweden during the Halloween 2003 storm, but it lasted only a few hours and affected only 50,000 people. Yet even without a major blackout since 1989, there has been plenty of damage to other segments of our technology not as lucky as our electrical power grid.

Satellite outages reported during the sunspot cycle of 1996-2007 rendered 18 satellites disabled, at a cost of nearly $3 billion. Many research satellites have been frequently rendered temporarily unusable by powerful solar flares and particle storms. During the Halloween 2003 storm, no fewer than 46 severe satellite problems were documented. Most of these were followed by a full recovery, but several resulted in permanent satellite damage.

International Space Station astronauts had to take cover during the November 4, 2003 storm events, yet still reported high radiation doses that were about twice the normal levels. Long duration human voyages to Mars would no doubt encounter quite a few flares. We know what to expect from them because we have been this way many times before with unmanned spacecraft.

Even now, Mars-orbiting satellites have reported that this environment is about twice as ‘hot’ as the one near the International Space Station. Upon arrival at Mars, astronauts would have to be shielded round-the-clock to reduce their cumulative radiation dosages to the recommended safe levels. But you don't have to be an astronaut to worry about solar storm radiation. During the Halloween Storm, the Federal Aviation Association instructed passenger jets flying Arctic polar routes to do so at lower than normal altitudes to make the trip safer for passengers and crews.

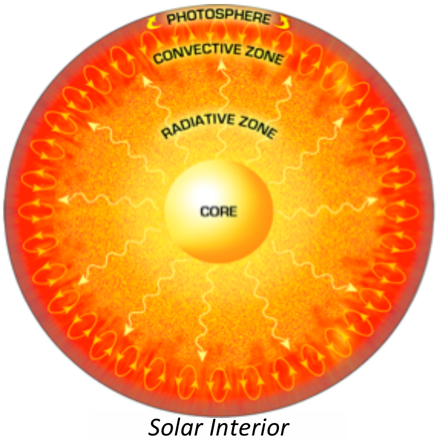
Keeping Close Watch on the Sun

The story of human lives crossed by solar storms, and what lies in store for us in the future, began in the closing days of summer in the year 1859. Like so many other natural phenomena, solar storms and the beautiful aurora that often accompany them, have been known to us for a long time. And as with many of the other natural disasters, they first began as annoyances, only to become severe problems as population pressure and advancing technology relentlessly placed us into closer conjunction with them.

Today we care deeply about the effects that space weather can have on our way of life. Space agencies have placed numerous instruments on a variety of satellites that are keeping a close eye on the Sun, watching its every flicker. These missions help us determine how the inside of the Sun works, how energy is stored and released in the Sun's atmosphere, and how to track the flow of energy and particles from the Sun to the Earth.

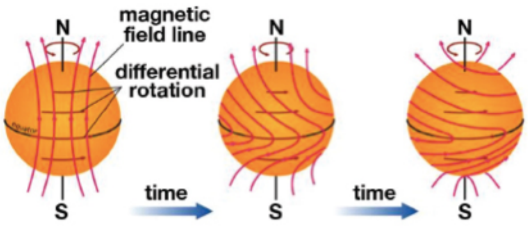
By better understanding the Sun and how it works, we can better predict solar storms and provide earlier warnings to help protect ourselves and our technologies from that weather out in space.

How Flares and Coronal Mass Ejections (CMEs) Wreak Havoc



Solar Interior

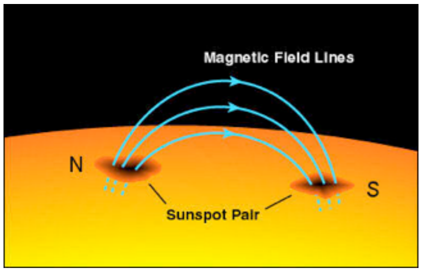
It all starts with sunspots. Sunspots are the visible footprints in the **photosphere** of relatively strong magnetic fields that emerge from below the **photosphere**. The Sun's magnetic fields are generated in its **convective zone**. See the illustration "*Solar Interior*."



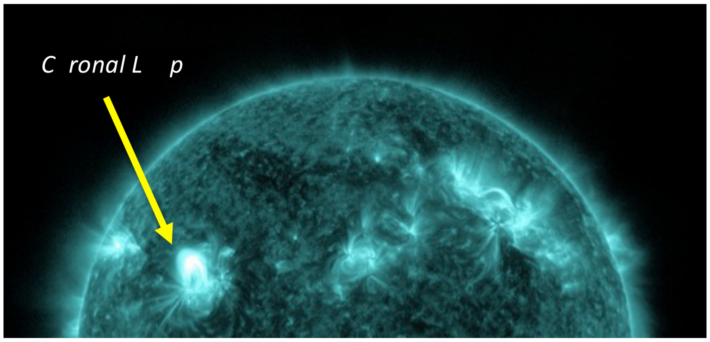
Magnetic fields lines warp and twist over time.

Since the Sun spins faster at its equator than at its poles, its magnetic field lines become warped and twisted, sometimes causing part of a magnetic field line to pop through the photosphere. It takes roughly 11 years for the Sun to move through the **solar cycle** that is defined by an increasing and then decreasing number of sunspots.

Sunspots usually come in pairs, one with a north polarity and one with a south polarity. Magnetic field lines are defined as having north and south polarity, even though geographic north (or south) might not be the actual direction they follow. For example, a bar magnet has magnetic field lines running from one end of the magnet to the other; one end is designated as "north," and the other end is designated as "south." You can hold a bar magnet in any orientation, and it always has a north end and a south end. This ToolKit uses compasses to illustrate magnetic fields and what directions they flow.



Solar Flares and Solar Storms



Material from the Sun's corona (or atmosphere) gathers around the magnetic field lines over the sunspots, glowing hot and bright in ultraviolet radiation, forming coronal loops.

The corona is a plasma – material that is so hot that the negatively charged electrons are ripped from the positively charged nuclei of the atoms, resulting in material that is electrically charged (filled with positively and negatively charged particles).

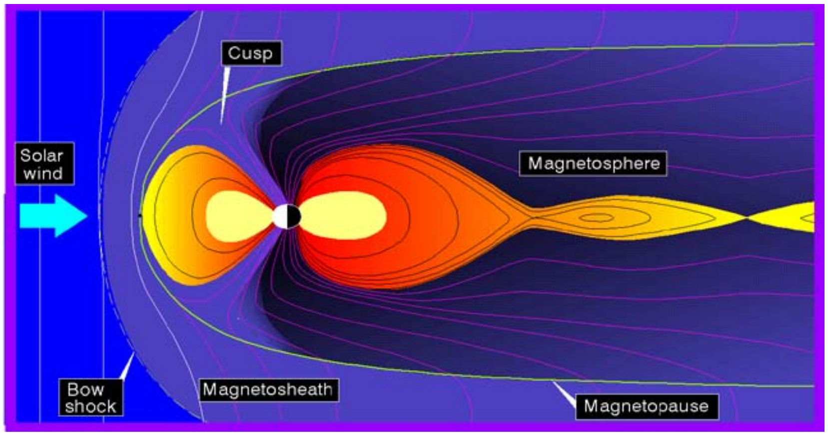
If the coronal loops change and twist, the coronal material can behave somewhat like a short circuit, causing an explosive flare-up called a "**solar flare.**" A flare can release X-rays that reach Earth in just over 8 minutes (because X-rays are a form of light energy and therefore also travel at the speed of light). If the explosion is large enough, a cloud of charged particles can escape the Sun and travel out into the Solar System. If that happens, the cloud of charged particles is called a "**Coronal Mass Ejection**" or **CME**. In this ToolKit, to reduce the use of jargon in public presentations, CMEs are referred to as "**solar storms**."

When a powerful **solar flare** occurs, the X-ray energy from the flare, if directed toward Earth, can strike the dayside of Earth's atmosphere, heating it and causing the atmosphere to expand. This can cause atmospheric drag for satellites in low-Earth orbit. X-ray energy can also suddenly interrupt signals from satellites, such as GPS. The radio communications disruptions caused by a solar flare are often due to the reaction of the ionosphere to the X-rays. Signals from satellites are degraded and scattered as the signal passes through the ionosphere that has been deepened by all the X-rays. This radiation can also pose a danger to space-walking astronauts.

When a **solar storm** (CME – a cloud of charged particles) occurs, it can sometimes be directed toward Earth. Depending on how fast the storm is traveling, it can take one to three days for that cloud of particles to cross the 93 million miles to Earth.

The first thing to remember about the effects of a solar storm (CME) striking Earth is that the particles (electrons and protons) in the solar storms do not directly enter the Earth environment because the Earth's magnetic field deflects them. It's the interaction of the solar storm with Earth's magnetic field that wreaks havoc.

Earth's **magnetosphere** (the region around Earth influenced by Earth's magnetic field) creates radiation belts of high-energy particles, and a solar storm can make these radiation belts (the Van Allen belts) extra dangerous. The solar storm can impart energy to the magnetosphere, which can cause electrons and protons in the magnetosphere to be accelerated to very high speeds. These fast-moving particles can impact satellites, potentially causing damage.



Detectors (particle and CCD) on satellites can also be degraded in sensitivity by exposure to the high-energy particles over time.

Earth's magnetic field can be disturbed and shifted by the impact of the solar storm. Shifting, moving magnetic fields induce electrical currents (illustrated in the activity, *The Magnetic Connection*, in this ToolKit). Those magnetic disturbances induce electrical currents in Earth's atmosphere, high in the ionosphere. It is called the ionosphere because it is filled with free electrons and ions – atoms and molecules that have charge because many of the atoms have lost one or more electrons. The ionosphere is electrically charged and has much higher density than the solar storm (CME) cloud.

The solar storm then can enhance the aurora and affect the power grid. This is basically a chain of magnetic-electric inductions:

1) The Earth's magnetic field absorbs energy from solar storm (CME) impact, which induces electric currents in the charged particles of Earth's magnetic field.
2) Those currents are directed along magnetic field lines toward Earth's polar regions and into the atmosphere and create the aurora.
3) Since the current is dynamic, the magnetic field it produces is also dynamic, which, once again, induces electric fields on the surface of Earth that will drive currents in anything that will conduct them, like oil pipelines and electrical grids.

If the current induced in the electrical grid is too high, it can blow out transformers and take down either the entire grid or just parts of it. This has plunged cities into darkness, as it happened in Canada in 1989.

Solar flares and solar storms (CMEs) can affect life on Earth in different ways. Both solar flare X-rays and the CME particles can directly and indirectly affect satellites, including interrupting their signals and changing their orbits.

Why Does the Sun Have Magnetic Fields?

This is still an active area of research. For a thorough discussion, refer to this article on the Sun-Earth Day website:
http://sunearthday.nasa.gov/2008/TTT/60_magfield.php

Why Does the Earth Have a Magnetic Field?

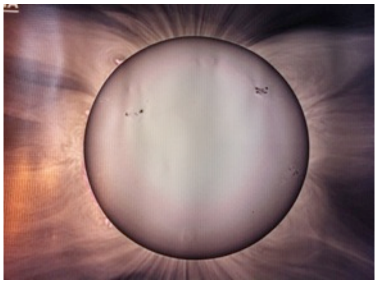
Adapted from NASA's Goddard Space Flight Center:
http://image.gsfc.nasa.gov/poetry/magnetism/magnetism.html

Although the Earth's crust is solid, the core of the Earth is surrounded by a mixture of molten iron and nickel. The magnetic field of Earth is caused by currents of electricity that flow in the molten core. These currents are hundreds of miles wide and flow at thousands of miles per hour as the Earth rotates. The powerful magnetic field passes out through the core of the Earth, passes through the crust, and enters space.

If the Earth rotated faster, it would have a stronger magnetic field. If it had a larger liquid core, Earth would also have a stronger magnetic field. By the time the field has reached the surface of Earth, it has weakened a lot, but it is still strong enough to keep your compass needles pointed towards one of its poles.

A compass works the way it does because Earth has a magnetic field that looks a lot like the one in a magnet. The Earth's field is completely invisible, but a compass needle on the Earth's surface can feel it, and it reaches thousands of miles out into space. If you were to study the Earth's invisible magnetic field from space, it wouldn't really look like the magnetic field around a bar magnet at all. Earth's magnetic field gets stretched out into a comet-like shape with a tail of magnetism that stretches millions of miles behind Earth, opposite from the Sun.

What Color Is the Sun Really?



The Sun is really white. This ToolKit shows images of the Sun in a variety of colors. Color is used to enhance features and distinguish wavelengths.
The Sun's true color though is white, as depicted in the lower image on the banner, which is a composite of the white light image (Photosphere) superimposed over an image of the corona from a solar eclipse.

Discussion of Models and Their Usefulness

These materials include models to demonstrate a variety of concepts. Models are useful, but their utility is always limited in some ways. It is often helpful to discuss the strengths and limitations of models with your visitors. For example, the nine-inch half-sphere in the ToolKit represents the Sun. What are some of its strengths as a model? How is it useful? Where does this NOT represent reality? What can't it be used for? These are questions you might want to include in your discussions with your visitors as they explore the Sun with these materials.

What Are QR Codes?

(adapted from an article on http://socialmediadiyworkshop.com)

The Banner as well as some of the "Explore the Sun" cards have QR Codes on them, like the one here on the right. If you are unfamiliar with these, here is a little bit of background information. This one on the right links to current views of the Sun from the Solar Dynamics Observatory:
http://sdo.gsfc.nasa.gov/data/

QR (for Quick Response) codes are a shorthand way to represent information, commonly used to store special website addresses. Smartphones can read these codes with specialized software (apps) installed on the phone. Using the app, you scan the code with your cell phone camera, and the QR code software uses the phone's network to take you to the Internet address hidden in the code. This process is also known as mobile tagging.

Where Could I Use These Activities?

MEDIA / RESOURCE	Solar Viewing	Indoor Public Event	Girl Scouts / Youth Group Meeting	Classroom			Club Meeting	Gen Public Presentation (Seated)
				K-4	5-8	9-12		
Training DVD							√	
Manual & Resources CD							√	
Sun in a Different Light Banner and Model	√	√	√		√	√	√	√
Explore the Sun Cards	√	√	√		√	√	√	
Magnetic Connection Box	√	√	√		√	√	√	
Protection from Ultraviolet	√		√	√	√	√		
Where Does the Energy Come From? Cards	√	√	√	√	√	√	√	
PowerPoint: Space Weather		√	√		√	√	√	√