SOLAR STORMS EFFECTS ON NUCLEAR AND ELECTRICAL INSTALLATIONS

2/17/2018

> "There are only two kinds of people who are really fascinating: people who know absolutely everything, and people who absolutely know nothing."
> Oscar Wilde, Irish author.

INTRODUCTION

The Earth is subject to an 11-year cycle of periods of increased solar activity, as astronomers have known for centuries. They are associated with visible sun spots on the surface of the sun. The events begin with thermonuclear explosion on the sun that swell up and bursts open on the sun's surface, releasing radiation and charged particles trapped in the solar wind. The charged particles have a speed of 4 million miles per hour (mph) when they reach the Earth. In solar flares, the emitted radiation covers the entire electromagnetic spectrum of radio waves, microwave, x-rays, gamma rays, as well as ultra-violet (UV). These electromagnetic bursts reach the Earth about eight minutes after leaving the sun. Proton storms follow taking about four hours to reach the Earth.

The continuous but variable flow of particles and magnetic fields from the sun creates gusts that can quickly reach the Earth. Within hours, a Coronal Mass Ejection (CME), accompanied by an Aurora Borealis or "Northern Lights" or an Aurora Australis or "Southern Lights" bombards the Earth with geomagnetic disturbances.

Solar storms can disrupt communication and navigational equipment, damage satellites, and even cause blackouts by damaging power plants and electrical grid components. In 1972, AT&T had to redesign its transatlantic cable power system after a major solar flare that made interstate phone communication impossible. In 1989, a strong solar storm knocked out the power grid in Québec, Canada, causing 6 million people to lose power. Solar storms can bring additional radiation around the north and south poles; a risk that forces airlines to reroute flights.

Figure 1. Blackout of August 14, 2003, before and after in the central and eastern USA and Canada. Source: NOAA.
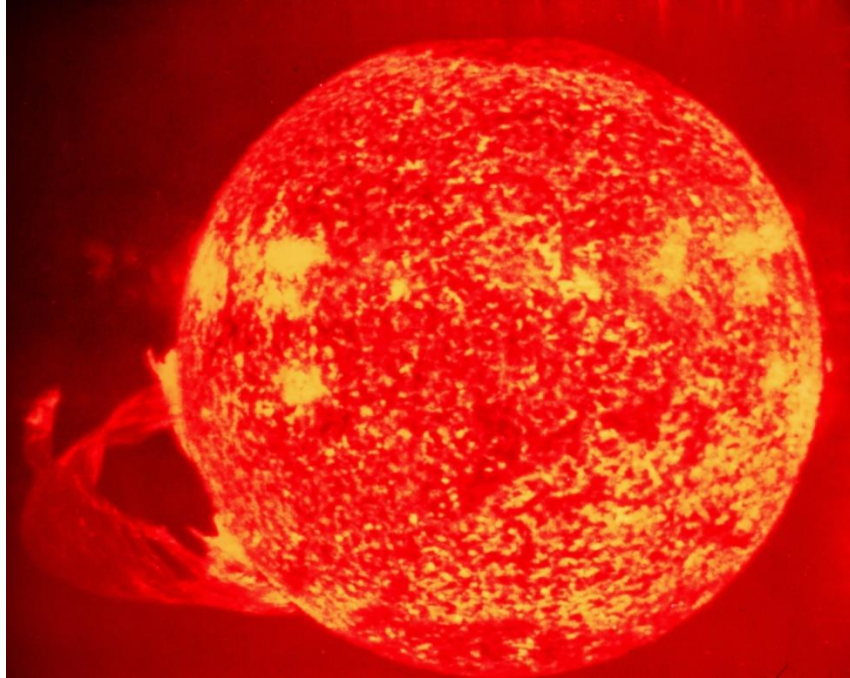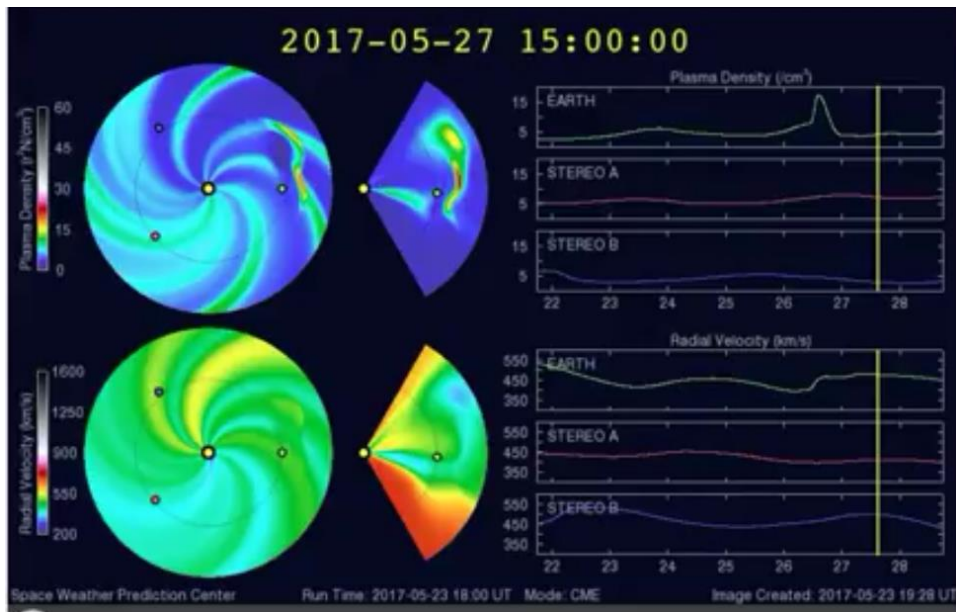
Figure 2. Solar flare showing the thermonuclear reactions in sun spots and the magnetic fields eminences. Source: NASA.
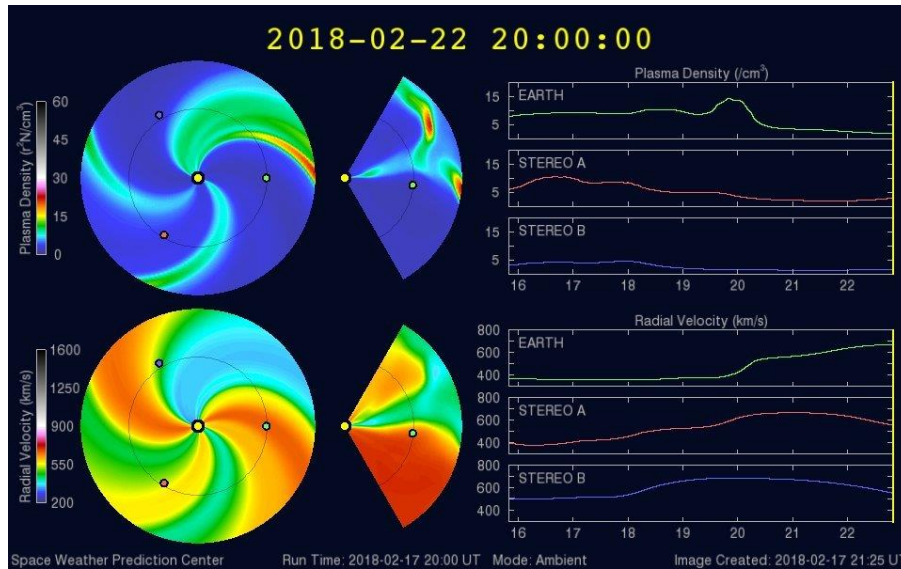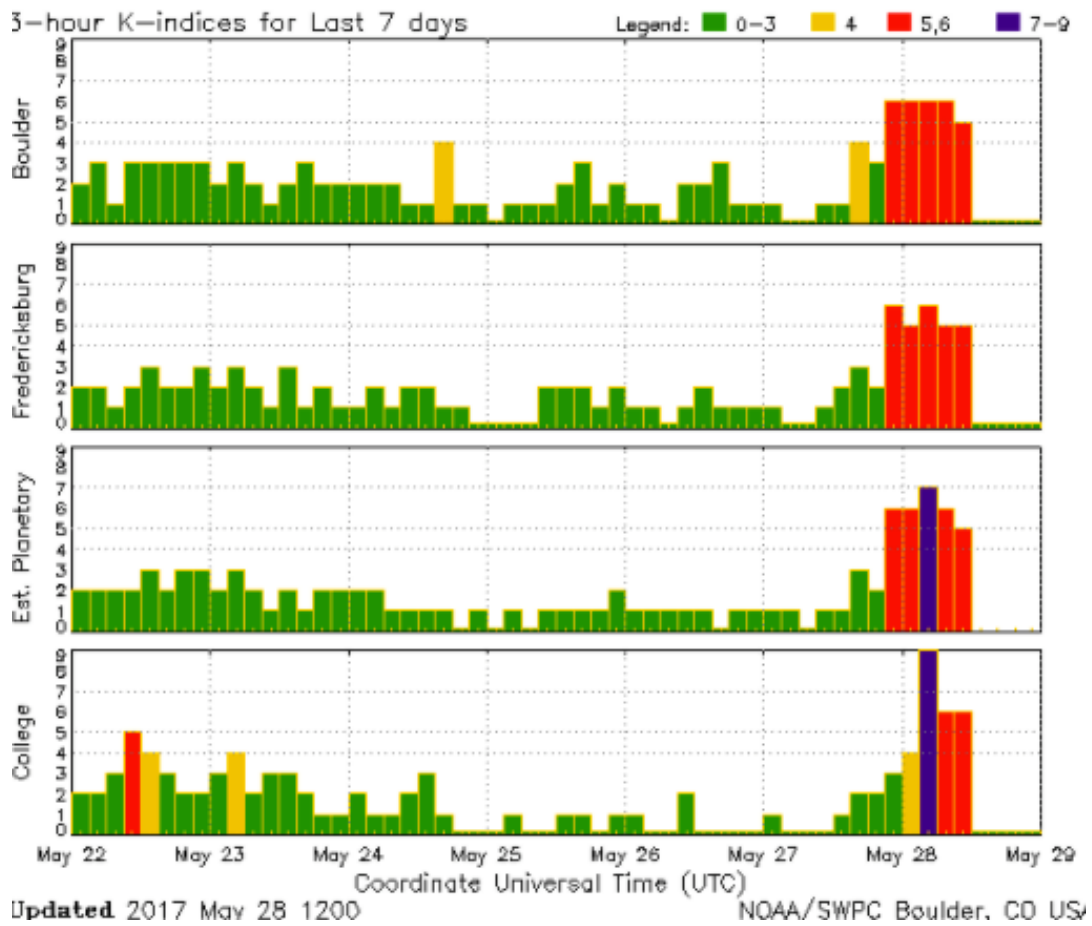
Figure 3. Coronal Mass Ejections (CMIs) hitting Earth, May 27, 2017, and February 17, 2018. Source: NOAA.
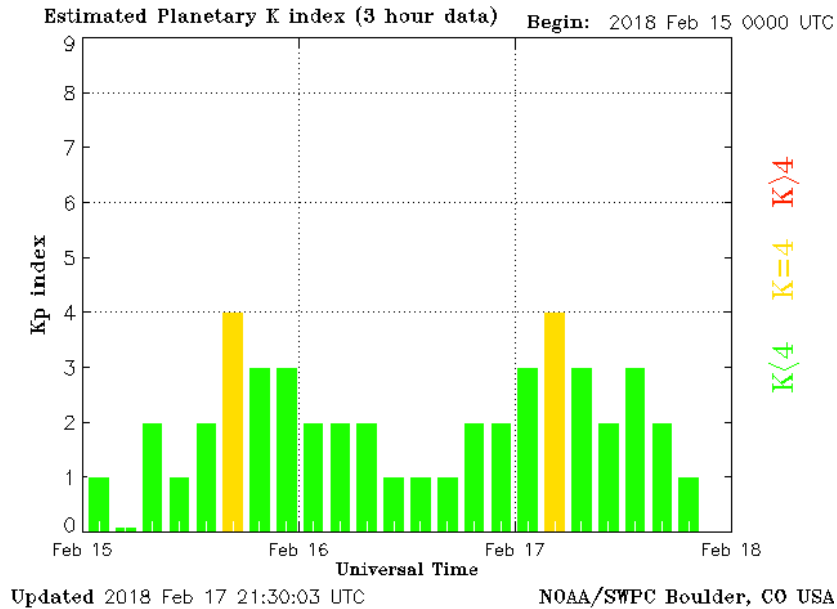
Figure 4. Geomagnetic Planetary K-index at different locations around May 28, 2017. A coronal mass ejection (CME) produced during the early UTC hours of May 23, 2017 hit Earth's magnetic field at 15:36 UTC on May 27, more than 24 hours after it was expected. Although the solar wind speed was relatively slow, the embedded magnetic field had a prolonged period of southward Bz that managed to spark a G3 – Strong geomagnetic storm. Planetary K-index at Boulder, Colorado, February 17, 2018. Source: NOAA.

POSSIBLE EFFECTS

On July 23, 2012, Earth had a near miss with a Coronal Mass Ejection (CME), from the most powerful storm on the sun in over 150 years. The Earth missed a direct hit through lucky timing as the sun's aim narrowly turned away from the Earth. Had it occurred a week earlier, it would have hit the Earth.

It is believed a direct CME hit would have the potential to seriously damage the communication networks, the Global Positioning System (GPS) and electrical grids to cause widespread blackout. It could disable anything that plugs into a wall socket. Water supplies largely rely on electric pumps and would also be damaged.

According to a study by the National Academy of Sciences, the total economic impact could exceed $2 trillion or 20 times greater than the costs of a Hurricane Katrina. Electrical transformers damaged by such a storm might take years to repair."

Physicist Pete Riley, published a paper titled "On the probability of occurrence of extreme space weather events," that calculated that the odds of a solar storm strong enough to disrupt our lives in the next 10 years is 12 percent.
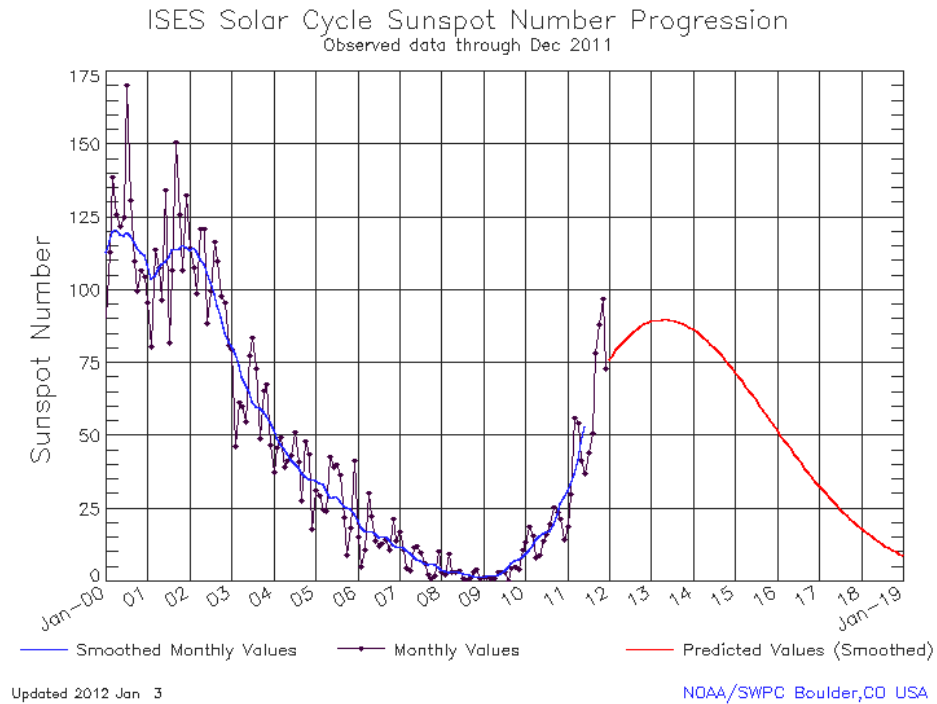
Figure 5. Solar sunspots cycle prediction. Source: NOAA.

Solar storms have effects on:

1. Radio communications fadeouts,
2. Auroras Borealis and Australis,
3. Disruptions in electrical grid power lines,
4. Disruption in radio transmission,
5. Geomagnetic storms,
6. Ionospheric storms,
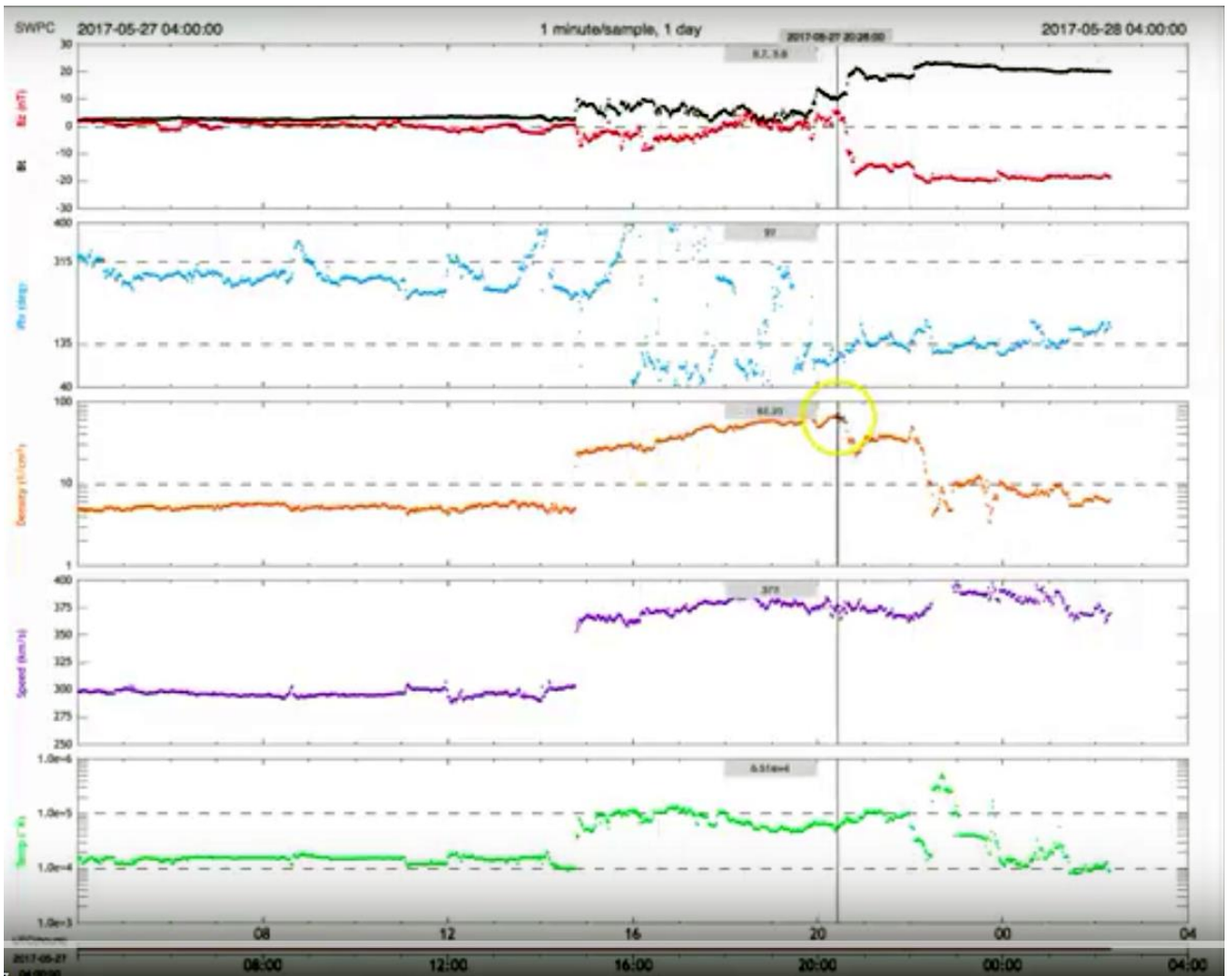7. Radiation hazards to astronauts.
8. Power plants shutdowns.

Figure 6. Real time solar storm density, speed and temperature. May 27, 2017. Source: NOAA.
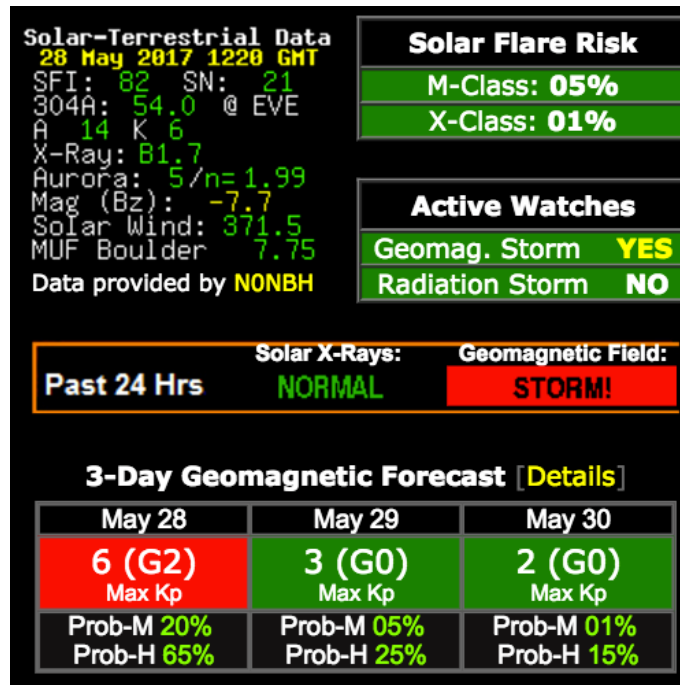
Figure 7. Solar-Terrestrial geomagnetic data. Source: NOAA.
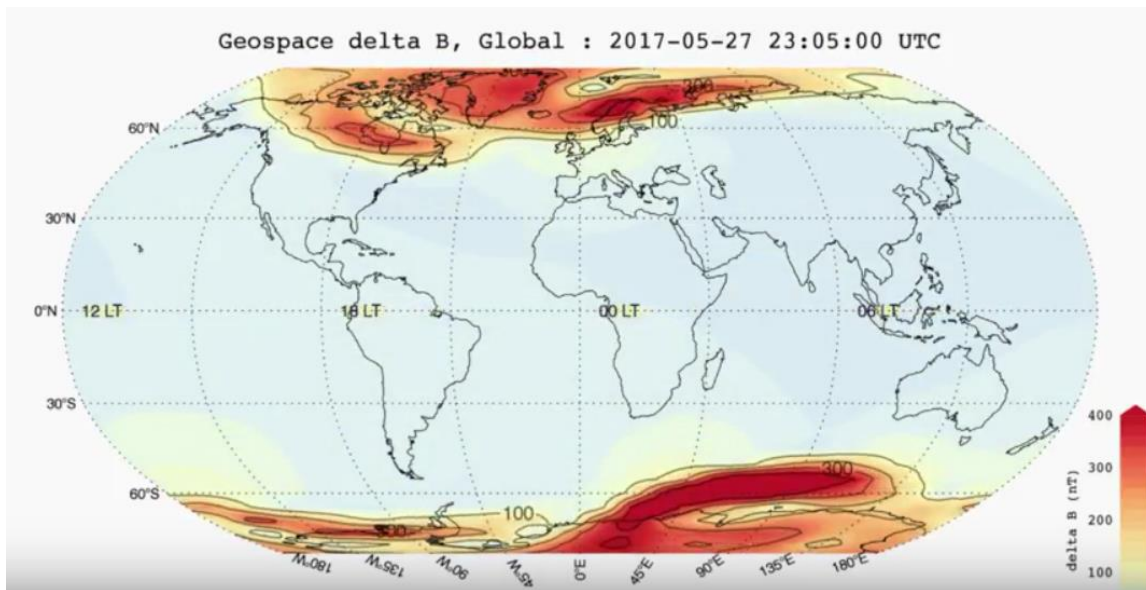

Figure 8. Geomagnetic storm. May 27, 2017. Global view. Storm affected airlines when British Airways had to cancel all flights. Power outages occurred in Karachi, Pakistan. Source: NOAA.
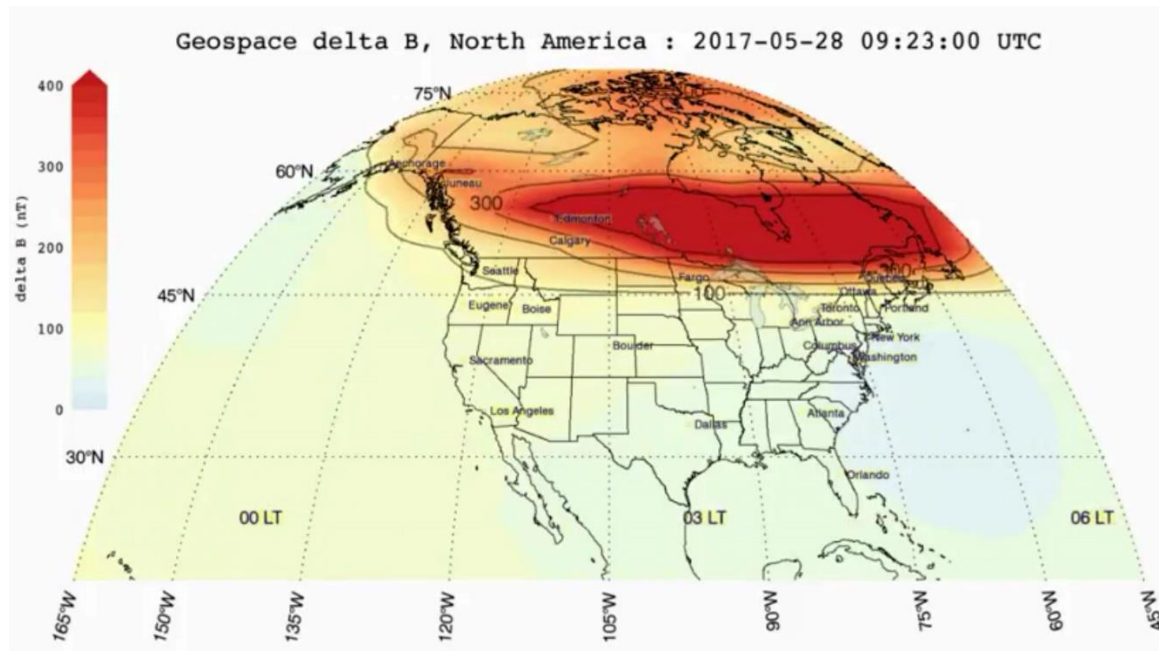
Figure 9. Geomagnetic storm. May 27, 2017. North American view. Power outages occurred to Ameren-Illinois, Kenosha, Wisconsin. Source: NOAA.

Under G3 – Strong geomagnetic storm (K-index of 7) threshold, the area of impact is primarily poleward of 50 degrees Geomagnetic Latitude. Power system voltage irregularities are possible and false alarms may be triggered on some protection devices. Spacecraft systems may experience surface charging and increased drag on low Earth-orbit satellites and orientation problems may occur. Intermittent satellite navigation (GPS) problems, including loss-of-lock and increased range error may occur. HF (high frequency) radio may be intermittent, aurora may be seen as low as Pennsylvania to Iowa to Oregon.

SOLAR STORMS PROGRESSION

Solar storms affecting the Earth progress in three stages, not all of which occur in any given storm:

1. High energy x-rays and ultraviolet radiation ionizes the Earth's upper atmosphere, interfering with radio communications.
2. Fast protons and electrons charged particles form a radiation storm, potentially affecting astronauts in Earth orbit.
3. A Coronal Mass Ejection (CME) of slower moving cloud of charged particles that can take several days to reach the Earth's atmosphere. When a CME hits the Earth's atmosphere, the solar particles can interact with the Earth's magnetic field to produce powerful electromagnetic fluctuations.

The most damaging emissions from solar storms travel slowly enough to be detected by sun-watching satellites well before the particles strike the Earth's atmosphere, giving about 20 hours of warning-time to allow for mitigating measures. For instance,

power companies could protect valuable transformers by taking them offline before the storm strikes. That would produce local blackouts, but they would not last for long.

CORONAL MASS EJECTIONS, CMEs

Coronal mass ejections stream toward Earth at more than 4 million mph. When they hit the Earth's magnetic field, they energize it and cause it to fluctuate. In a moderate or strong storm, these fluctuations can temporarily impair navigation, power, satellite and other electrical systems.

When such events are imminent, power grid managers and other electrical systems operators watch space weather forecasts. Satellite operators switch into a standby mode and temporarily forgo communication between ground control and spacecraft in orbit to prevent the garbling of messages. Airlines reroute planes that normally follow the fuel-saving polar routes. Along those routes, pilots depend on High Frequency (HF) radio communications that are vulnerable to disruptions by space weather.

Expecting a major disruption, on Monday, January 23, 2012 airlines rerouted airplanes flights away from the poles. Radio communications were hampered by the strong radiation storm. Some "soft" or correctable errors occurred on satellite systems that are associated with the solar radiation storm.

SOLAR WIND AND SOLAR STORMS

Figure 10. Solar Coronal Mass Ejection (CME) interaction with The Earth's magnetic field. Source: NASA/Goddard.
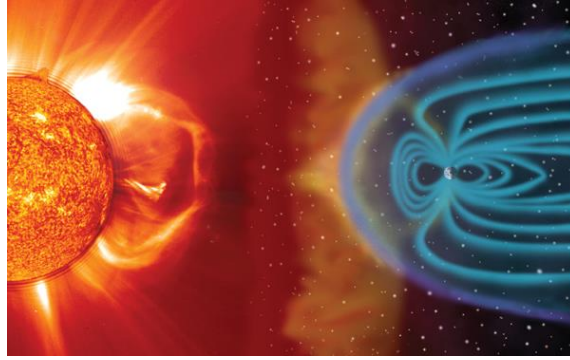
Figure 11. Solar wind and storms interaction with the Earth's magnetic field. Note that the sun is one million times the size of the Earth. Source: NOAA.
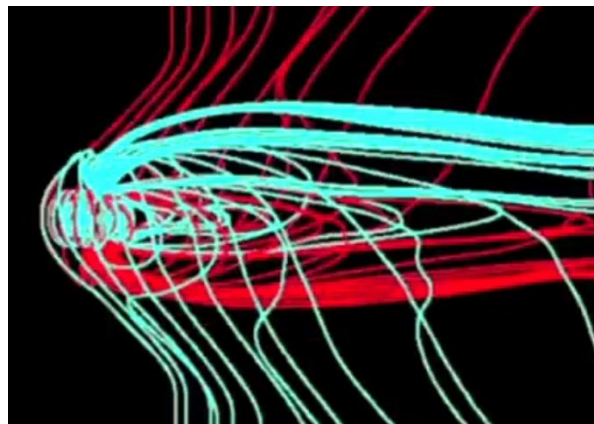
Figure 12. Charged particles trajectories in the Earth's magnetic field.
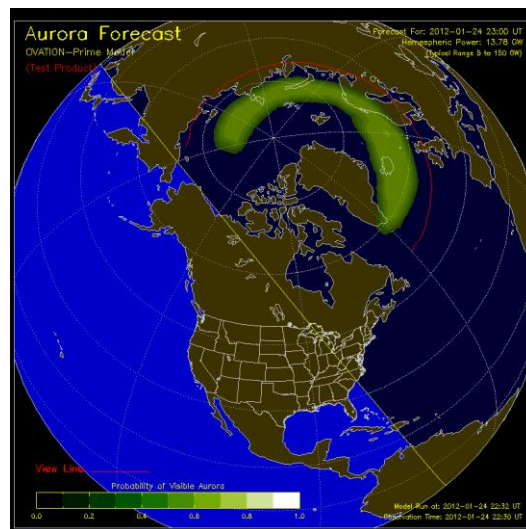
Figure 13. Aurora Borealis space weather forecast, January 24. 2012. The sunlit side of Earth is indicated by the lighter blue of the ocean. The sub-solar point is also shown as a yellow dot but only if the sub-solar point is in the view of the chosen image. The day-

night line or terminator is shown as a yellow line. The red line about 1,000 km equatorward of the aurora indicates how far away viewers on the ground might see the aurora assuming good viewing conditions. Source: NOAA.
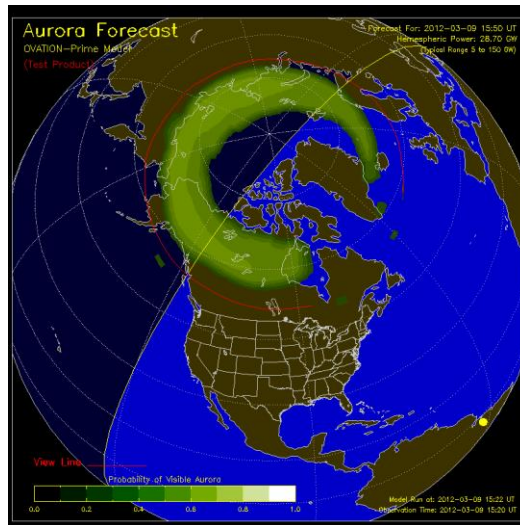
Figure 14. Aurora Borealis space weather forecast, January 24. 2012. The graph shows the intensity and location of the aurora as expected for the time shown at the bottom of the map. The forecast is based on current solar wind conditions and the average time for the solar wind to propagate from the ACE satellite at L1 to Earth. The model produces an estimate of the intensity of the aurora. In this product a linear relationship between intensity and viewing probability is assumed. This relationship is validated by comparison with data from the UVI instrument on the NASA POLAR Satellite. Source: NOAA.

Figure 15. Aurora Borealis in Tromsoe, Northern Norway from the January 2012 event. Source: NOAA.
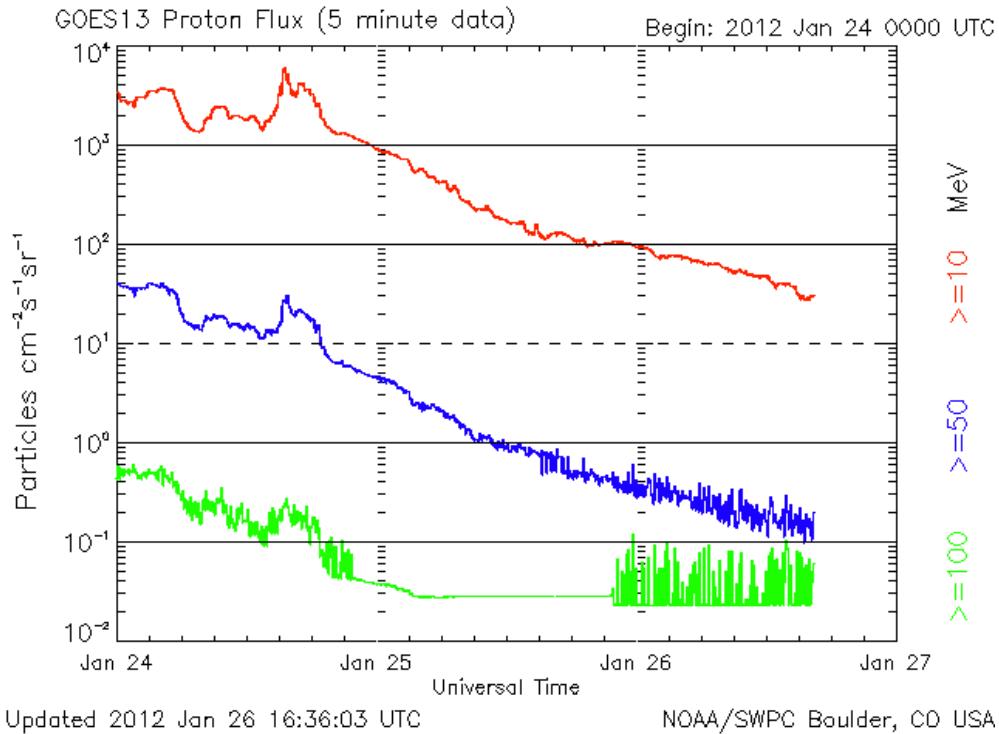
Figure 16. GOES Satellite 5-minute averaged integral proton flux (protons/cm2-s-sr) as measured by the SWPC primary GOES satellite for energy thresholds of >=10, >=50, and >=100 MeV. SWPC's proton event threshold is 10 protons/cm^2-s-sr at >=10 MeV. Large particle fluxes have been associated with satellite single event upsets (SEUs). Source: NOAA.

A solar storm has a bow shock that is stopped by the Earth's protective magnetosphere. The magnetic cloud of plasma can extend to 30 million miles in width by the time it reaches the Earth.

The magnetic field orientation of a Coronal Mass Ejection (CME) is a major factor as to whether the Earth will suffer many consequences from any given CME. After a CME blasts from the sun towards Earth, a cloud of charged particles impacts our magnetosphere within 2 to 4 days.

Figure 17. Coronal Mass Ejection (CME) 2002. Source: Solar Dynamic Observatory (SDO) NASA.

Figure 18. Coronal Mass Ejection (CME), June 7, 2011. Source: Solar Dynamic Observatory (SDO) NASA.

The Earth is effectively electrically connected to the sun by a large-scale circuit. The consequences are dramatic: disruptions to communications satellites, interference with Global Positioning Systems (GPS) and air traffic control. The phenomenon can take down the high-voltage electric transmission system over wide swaths of the planet, blacking-out more than 130 million people in the USA alone.

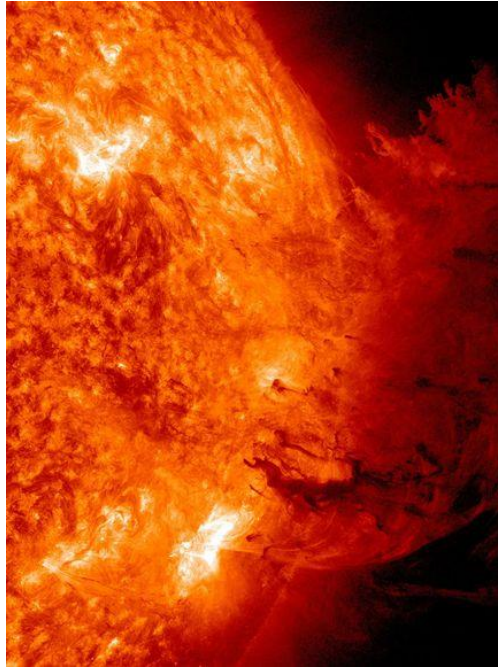Secondary effects due to the loss of the electrical grid involve nuclear power plants shutdowns, water system failures, severe disruptions to natural gas pipelines, factories shut down for weeks or months, food rotting in unrefrigerated warehouses, and costs to the world economy. The cost of the damage caused by a CME to the USA could total $1-2 trillion. More than 300 grounded electrical high-voltage transformers in the USA suffer damages so serious that they need to be replaced, putting intolerable strain on an already stressed supply chain.

Recovery takes as much as a decade, as the results would wreak havoc with the USA and world infrastructure and economy. This is fact, not science fiction according to the office of emergency response at the Federal Energy Regulatory Commission (FERC). It occurred before but with far less severe economic consequences. It is likely to happen again following a higher activity in the solar cycle.

EFFECT ON NUCLEAR POWER PLANTS

In 1989 a solar storm affected the Salem Pressurized Water Reactor (PWR) in New Jersey. The 1,160 MWe Salem-1 nuclear power plant is located on an artificial island at the mouth of the Delaware River, along with two other nuclear units.

The solar storm induced a large current into the PJM 500-kV transmission system, which damaged the Salem Unit 1 step-up transformer, resulting in a large melted mass of copper and copper shot.

The transformer's winding insulation confined the damage, and the plant did not trip-off during the solar flare. The plant operators discovered the damage after the storm. The transformer had to be replaced, at a cost of millions of dollars.

GEOMAGNETICALLY INDUCED CURRENT (GIC)

As the charged solar particles in the solar wind arrive at the Earth, they cause rapid fluctuations of the Earth's geomagnetic field. Induced Earth-surface potential and Geomagnetically Induced Currents (GICs), occur. GIC appears as a quasi-DC current or an AC waveform with a period of several minutes and appears as a DC current to the bulk electric grid system.

The consequences of this DC current are to drive transformer cores into saturation. This causes significant heating from stray flux, increases the Volts Ampère Reactive (VAR) power losses that depress system voltages, and can damage the transformer itself.

MULTIPLE CONTINCENCY INCIDENT (MCI)

The induced currents can precipitate a Multiple Contingency incident (MCI) which, under certain operating conditions, can jeopardize the integrity of the bulk electric systems in North America.

The harmonic currents can cause the over-current relays to trip the capacitor banks because capacitors offer a lower impedance path for the harmonics. The static VAR power compensators can trip for over-current or over-voltage protection.

The complex events resulting from the induced currents can take the electrical generators down along with the whole electric grid, as the electrical generators are not immune to the harmonic currents. Those units that do not trip are still susceptible to damage from turbine blade vibrations and possible blades ejection.

EFFECT ON THE NORTH AMERICAN POWER GRID, 1989

When a solar storm strikes the Earth's magnetosphere, it creates a gust in the solar wind. On Friday March 10, 1989 such a storm affected northern Canada in a matter of days. The arrival of the solar particles caused severe disturbances in the planet's magnetic field.

According to a description by NASA:

"On Friday March 10, 1989, astronomers witnessed a powerful explosion on the sun. Within minutes, tangled magnetic forces on the sun had released a billion-ton cloud of gas. It was like the energy of thousands of nuclear bombs exploding at the same time. The storm cloud rushed out from the sun, straight towards Earth, at a million miles an hour. The solar flare that accompanied the outburst immediately caused short-wave radio interference, including the jamming of radio signals from Radio Free

Europe into Russia. It was thought that the signals had been jammed by the Kremlin, but it was only the sun acting up!"

On March 13, 1989 seven static VAR compensators on Hydro-Québec's, HQ giant La Grande high-voltage transmission network shut down in a matter of seconds. An induced direct current from the solar storm caused the transmission system voltage to drop, frequency to rise, and the line to trip off.

The rest of the HQ transmission system collapsed in seconds. It took nine hours to restore 18,000 MWe of power to the network. The solar storm left considerable wreckage in its path, including two La Grande 4 generating station step-up transformers, thyristor and capacitor banks at several units, and static VAR compensators across the system that were damaged or destroyed.

The effects on the North American electrical grid that connects Canada and the USA, except for the state of Texas that is connected to the Mexico's electrical power grid, were significant.

The Québec blackout was not localized. Some of the USA electrical utilities were affected. New York Power Authority lost 150 MWe of capacity the moment the Québec power grid collapsed. The New England Power Pool lost 1,410 MWe at about the same time. Service to 96 electrical utilities in New England was interrupted while other reserves of electrical power were brought online.

The USA had some excess spare capacity at the time. Across the USA, 200 power grid problems erupted within minutes of the start of the March 13, 1989 solar storm, without causing a complete blackout.

EFFECT ON COMMUNICATION SATELLITES

Some communication satellites tumbled out of control in space for several hours. NASA's TDRS-1 communication satellite recorded over 250 anomalies as high-energy particles impacted the satellite's sensitive electronics.

In the Space Shuttle Discovery, a sensor on one of the tanks supplying hydrogen to a fuel cell was showing unusually high pressure readings on March 13, 1989. The problem went away just as mysteriously after the solar storm subsided.

Of particular concern are disruptions to the Global Positioning System (GPS), which has become ubiquitous in cellular phones, ships, airplanes, and automobiles. A $13 billion industry in 2003, the GPS system is predicted to grow to nearly $1 trillion by 2017.

GLOBAL EFFECTS, 1989

Large geomagnetic storms can have a global reach and produce impacts to other developed power grids around the world. In the UK, the March 10, 1989 storm is suspected to have caused damage to two 400 kV transformers. Since 1989, the operators of the UK power system equipped their grid with transmission system static VAR and switched-capacitance devices for system voltage regulation. This makes their system less vulnerable to future geomagnetic storms.

Recent and lower intensity storms reached the Southern Hemisphere producing lower intensity, but long duration GIC disturbances in South Africa that caused permanent damages and loss of 15 EHV transformers in the South African Eskom system.

EARLIER SOLAR STORMS EVENTS, 1859, 1921, 2003

The 1859 largest known storm, called the "Carrington Event," after the British astronomer Richard Carrington struck Earth. During the Carrington Event, Northern Lights were reported as far south as Cuba and Honolulu, while Southern Lights were seen as far north as Santiago, Chile. The flares were so powerful that people in the northeastern USA could read newspaper print just from the light of the aurora borealis. The geomagnetic disturbances were strong enough that USA telegraph operators reported sparks leaping from their equipment, with some setting equipment fires.

A space storm's impact is measured in nano-Teslas (nT). The lower the figure, the more powerful the storm. A moderate storm is around -100 nT; extreme storms log in around -300 nT. The Carrington solar storm was three times more powerful than the strongest space storm in modern memory; the one that cut power to an entire Canadian province, Québec, in 1989. The 1989 coronal mass ejection that centered on Québec measured -589 nT. Carrington's 1859 solar storm was estimated to have been -1,760 nT.

Another solar storm struck the Earth in May 1921, causing substantial destruction. Government experts have defined the 1921 storm as a 1 in a 100 years event. This does not mean it cannot happen more frequently than that, but gives an indication of its severity.

A minor solar storm in October-November 2003 took down the USA Federal Aviation Administration's new Global Positioning System, GPS-based navigation system for 30 hours and damaged electrical systems from Scandinavia to South Africa. These "Halloween Storms" of 2003 interfered with satellite communications, produced a brief power outage in Sweden, and lighted up the skies with ghostly auroras as far south as Florida and Texas.
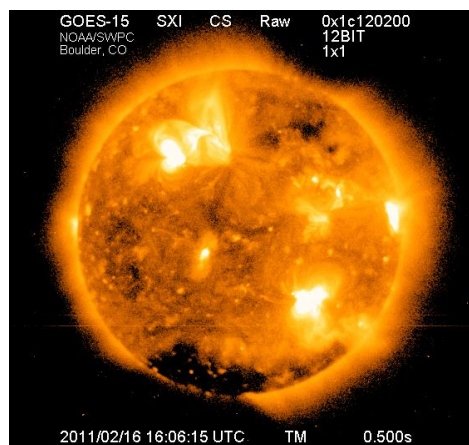
SOLAR STORM, 2011

Figure 19. Solar storm on February 16, 2011. Source: NOAA.

Bright and dark regions of the sun in appeared in a solar x-ray image at the NOAA's Space Weather Prediction Center showed enhanced solar wind on February 16, 2011 with magnetic storminess. Effects included temporary radio blackouts, re-routed airplanes, increased risk of damage to electrical grids and satellites and brilliant auroras.

SOLAR STORM, MARCH 2012

On March 6, 2012, X-class flares occurred. A double burst on March 6, 2012 was followed by another X1.1-class flare. A Coronal Mass Ejection (CME) associated with the R3 (Strong) Radio Blackout event from 0024 UTC March 7 (7:24 p.m. EST March 6) continued to affect the Earth and G3 (Strong) storming levels were observed. The magnetic field orientation needed to cause strong geomagnetic storming did occur overnight. It got off to a slow start and reached predicted levels. The Solar Radiation Storm levels remained at the S2 (Moderate) levels, flattening out in response to a new, R2 (Moderate) solar flare occurring at 0353 UTC March 9 (10:53 p.m. EST March 8). This R2 event had an associated CME with a resulting geomagnetic storm.
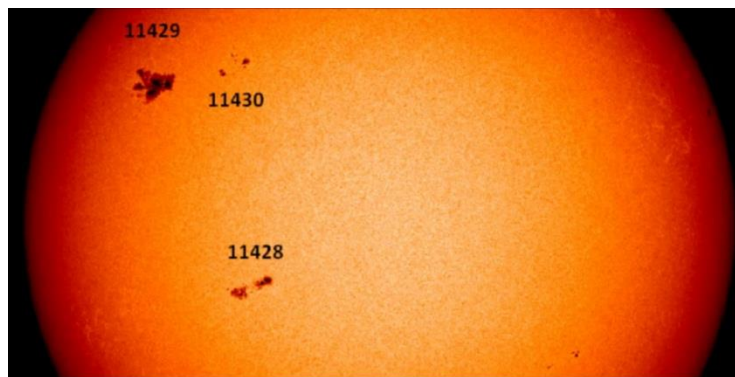
Figure 20. Solar flare visual picture on March 5, 2012 at the 11429 location. Source: NOOA.
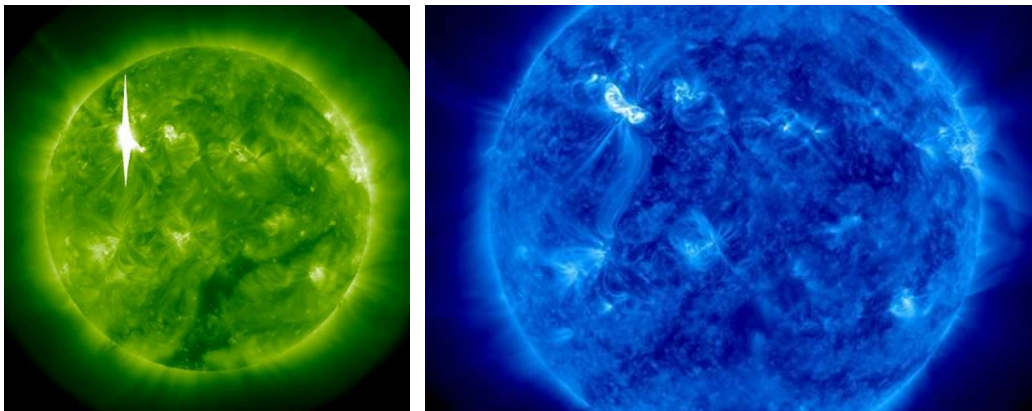
Figure 21. Infrared and x-ray pictures of the March 5, 2012, showing onset of the Coronal Mass Ejection. Source: NOAA.
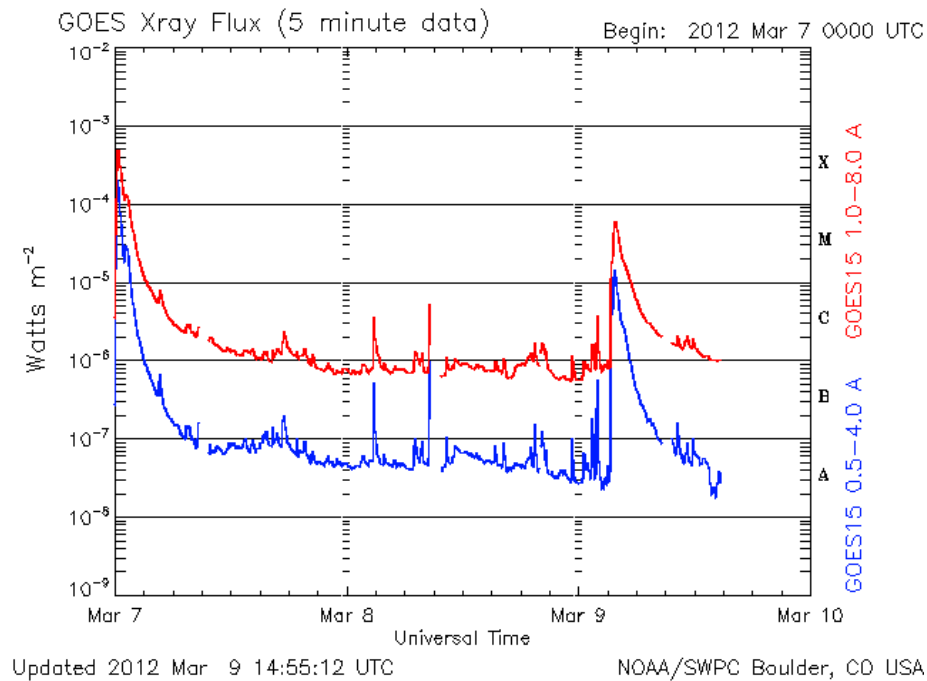
Figure 22. Plot showing three days of 5-minute solar x-ray flux values measured on the SWPC primary GOES satellite. One low value may appear prior to eclipse periods. Source: NOAA.

EFFECT ON MODERN ELECTRICAL SYSTEMS, INTERCONNECTEDNESS, CASCADE FAILURE

The big concern from solar flare is their possible impact on the electrical grid, since power surges caused by solar particles could blow out giant transformers. Such transformers can take a long time to replace, especially if hundreds are destroyed at once.

Figure 23. Damage to electrical transformers from the March 13, 1989 solar event.
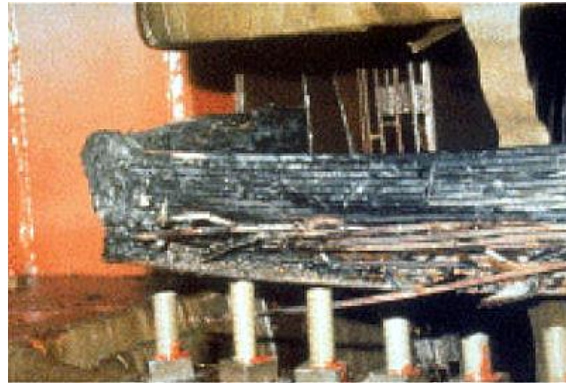
Figure 24. Transformer fire resulting from the March 13, 1989 solar event.

Modern storms can cause much more damage and disruption than earlier events, since the electrical and electronic infrastructures around the world are more ubiquitous, complex, and connected. Power grids may be more vulnerable than ever because of inter-connectedness. In recent years, utilities have joined grids together to allow for long-distance transmission of low-cost power to areas of sudden demand. Inter-connectedness makes the system susceptible to wide ranging "cascading failures."

Larger, longer, and bigger transmission systems add to the vulnerability to GICs, by reducing the resistance of the grid. The miles of high-voltage transmission voltage in the USA have increased by a factor of 10 over the last 50 years leading to an effectively larger antenna.

SOCIETAL AND ECONOMIC IMPACTS, PREPAREDNESS

Considering the potential effects of an event similar of the May 1921 storm on the modern USA grid system, the risks involved loss of more than 350 high-voltage transformers and power outages to more than 130,000 million Americans.

The loss of electricity would spread across the physical infrastructure and would include water distribution affected within several hours; perishable foods and medications lost in 12-24 hours; loss of heating/air conditioning, sewage disposal, phone service, and fuel re-supply.

The threat of geomagnetic storms is well understood in the electrical utility industry, and much effort is being devoted to understanding and preparing for this contingency.
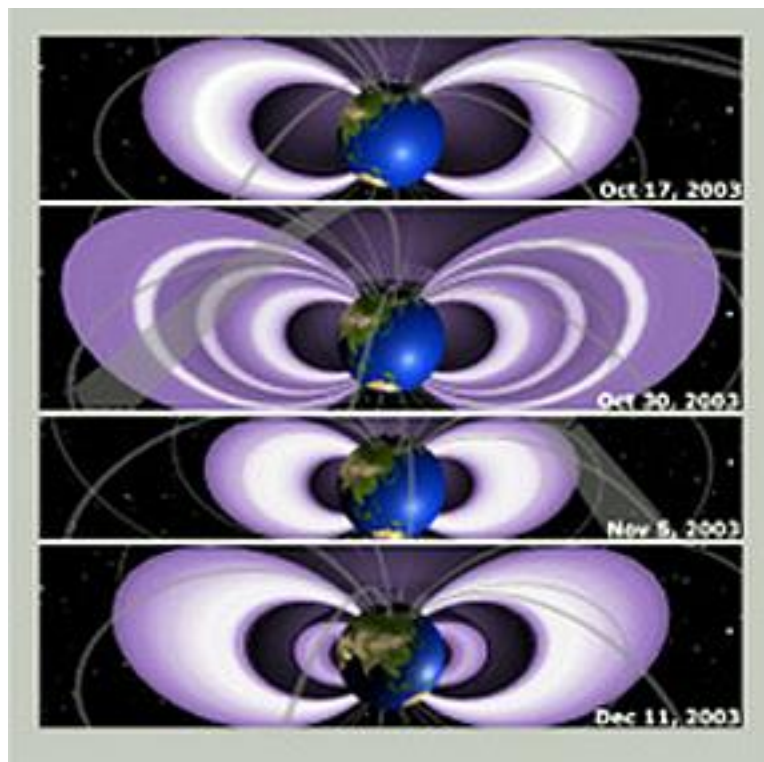
Figure 25. Solar storms effects on the Earth's protective Van Allen magnetic fields.
Source: NASA.

The Electric Power Research Institute, EPRI has been devoting considerable effort to studying geomagnetic storms since the 1989 event. It has produced voluminous work on the impacts of solar storms on electric systems, working through its SUNBURST project, which aims to "monitor, study, and mitigate" geomagnetically-induced currents on the power grid.

With the solar cycle just passing the minimum and solar storm activity at a 50-year record low in 2010, it was easy to temporarily forget about solar storms and GICs.

HIGH IMPACT LOW FREQUENCY (HILF) EVENTS

Solar storms, though potentially catastrophic, are not very predictable, in either frequency or strength. They represent what the utility industry calls High-Impact Low-Frequency (HILF) risks.

Solar storms are grouped with electromagnetic pulse events, which might be caused by the detonation of nuclear devices in the upper atmosphere by an adversary hoping to take down the high-voltage grid by causing an Electro Magnetic Pulse (EMP) event.

Other HILF risks in the utility planning process include conventional weather effects, including tornadoes and hurricanes.

Utilities have spent large amounts on preparations for HILF risks, but passing costs on to customers, either in advance, or after a catastrophe, will be difficult in a political environment characterized by an anti-rate-increase attitude.

The insurance company Zürich Services Corporation published an analysis of the exposure of various industries to solar storms, including the prospect of replacing large high-voltage, grounded transformers at $10 million a pop. The study concluded that a large solar storm would be an event "beyond insurance."

RECOVERY TRANSFORMERS, RecX PROJECT

EPRI and the Department of Homeland Security, DHS worked on a project to design prototype recovery transformers that could temporarily replace damaged equipment after a storm.

The Recovery Transformer, RecX Project would build and pre-position truck-mounted single-phase 345 kV transformers as temporary fixes if a conventional three-phase, 345- kV machine were damaged.

The idea is to design a transformer that is smaller and easier to transport and quick to install. The goal of the project is to produce solid-state transformers that are smaller and lighter and could be transported by helicopter.

Storms 10 times worse than the 1989 event can occur and have occurred and offer a significant challenge since it would be the largest natural disaster the USA could face and needs to survive.

HIGH-ALTITUDE NUCLEAR ELECTROMAGNETIC PULSE (HEMP); NUCLEAR ELECTROMAGNETIC PULSE (NEMP), HIGH POWER RADIO FREQUENCY (HPRF) DEVICES

The Electromagnetic Pulse (EMP) of an atmospheric nuclear burst (SNB) can trigger whistlers. The EMP radiation, its intensity peaking in the 10 kHz frequency range travels through the ionosphere wave guide and can leak upward into the magnetosphere along previously existing magnetic field-aligned whistler ducts.

In the Information Age, a Nuclear EMP attack that can disable the communications and computer networks and hence eliminate the second strike retaliatory ability of a potential opponent against a first strike, falls under the category of electronic warfare or information warfare, not nuclear warfare. The military doctrines of China and Russia define information warfare as embracing a spectrum ranging from computer viruses to nuclear NEMP attack. A state adopting a no-first-use policy, such as India, is compelled to

implement robust NEMP protections. A country that has lost its advanced technology capabilities to a NEMP attack, short of surrendering, would end up fighting with tactics and technology going back to the 19th century at a great disadvantage. India, Pakistan, and Israel possess missiles and nuclear weapons giving them the capability to make NEMP attacks against their regional adversaries.

An article in the "Indian Express" on 17 September 17, 1999, by a member of India's Institute of Defense Studies Analysis openly advocates that India be prepared to make a preemptive NEMP attack, both for reasons of military necessity and on humanitarian grounds:

> "A study conducted in the U.S. during the late 1980s reported that a high-yield device exploded about 500 kilometers above the ground can generate an electromagnetic pulse (EMP) of the order of 50,000 volts over a radius of 2,500 kilometers around the point of burst which would be collected by any exposed conductor. Such an attack will not cause any blast or thermal effects on the ground below but it can produce a massive breakdown in the communications system....It is certain that most of the land communication networks and military command control links will be affected and it will undermine our capability to retaliate. This, in fact, is the most powerful incentive for a preemptive attack. And a high-altitude exo-atmospheric explosion may not even kill a bird on the ground."

An NEMP attack is regarded by some analysts as a legitimate use of nuclear weapons, because NEMP would inflict no or few prompt civilian casualties. A NEMP attack appears to be a unique exception to the general stigma attached to nuclear weapons use by most of the international community in public statements. Some analysts in Japan and Germany; nations that historically have been most condemnatory of nuclear and other weapons of mass destruction in official and unofficial forums appear to regard an NEMP attack as morally defensible and a legitimate use of nuclear devices.

The USA's 1.44 Mt of TNT equivalent W49 warhead used for the "Starfish Prime" high-altitude test E3 component could have produced more than 5000 nTesla/min field strength. A disturbance in the USA of 4800 nTesla/min is estimated to likely damage about 365 large transformers in the power grid, and would leave about 40 percent of the USA population without electrical power for as long as 4 to 10 years due to the loss of large transformers that would have to be custom-built in other countries if power was not available for the two USA plants that are able to make these transformers [3].

Figure 26. "Starfish Prime" nuclear test on July 8, 1962, a part of "Operation Fishbowl," at Johnston Island as observed at Honolulu, Hawaii, 897 miles away. It damaged 300 street lights [3].

Underground power lines can be affected. Overhead power lines wire insulators would be damaged, resulting in a short circuit on the power lines and some power lines detaching from the poles and falling to the ground.

At a testimony before the USA Congress House Armed Services Committee on October 7, 1999, Dr. Lowell Wood, describing the Starfish Prime and the related EMP-producing nuclear tests in 1962, stated [3]:

> "Most fortunately, these tests took place over Johnston Island in the mid-Pacific rather than the Nevada Test Site, or electromagnetic pulse would still be indelibly imprinted in the minds of the citizenry of the western U.S., as well as in the history books. As it was, significant damage was done to both civilian and military electrical systems throughout the Hawaiian Islands, over 800 miles away from ground zero. The origin and nature of this damage was successfully obscured at the time -- aided by its mysterious character and the essentially incredible truth."

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APPENDIX I

VOLT AMPERE REACTIVE, APPARENT POWER Q

In Alternating Current, AC power transmission and distribution, the Volt Ampère Reactive power or VAR is a unit used to measure the apparent reactive power Q in an AC electric power system where:

$$\text{Reactive Power } Q = V_{rms}.A_{rms}\sin\phi$$
$$\text{where: } V_{rms} = \text{rms voltage}$$
$$A_{rms} = \text{rms current}$$
$$\phi = \text{phase angle between voltage and current}$$

(1)

Since AC power has a varying voltage, efficient power systems must vary the current in synchrony with the voltage.

VARs measure the unsynchronized "leading or "lagging" currents. VARs are the product of the root mean square, rms voltage and current, or the apparent power, multiplied by the sine of the phase angle between the voltage and the current.

When the phase angle between the load voltage and load current is out of phase by 90 degrees, this defines the VAR-reactive as:

$$VAR = V_{rms}.A_{rms}\sin 90^o = V_{rms}.A_{rms}[\text{Volt.Ampere}]$$

(2)

Note that the apparent power Q is different from the real power P.

APPENDIX II

NOAA SPACE WEATHER SCALE FOR GEOMAGNETIC STORMS

The K index is a 3-hourly quasi-logarithmic local index of geomagnetic activity relative to an assumed quiet-day curve for the recording site. Its range is from 0 (quiet) to 9 (severely disturbed). The K index measures the deviation of the most disturbed component.

The Kp is an index used to indicate the severity of the global magnetic disturbances in near-Earth space. It is based on the average of weighted K indices at 13 ground magnetic field observatories. It is based on the range of the magnetic field variation within 3 hour intervals that is caused by phenomena other than the diurnal variation and the long-term components of the storm time variations. The values of the Kp range from 0 (very quiet) to 9 (very disturbed) in 28 discrete steps, resulting in values of 0, 0+, 1-, 1, 1+, 2-, 2, 2+,...9.

An Estimated Kp is calculated by NOAA in near-real-time. The official, after-the-fact, 3-hourly planetary index of geomagnetic activity is calculated twice per month by the

German GeoForschungsZentrum (GFZ) (Research Center for Geosciences), from the K indexes observed at 13 stations primarily in the Northern Hemisphere. The Kp indices, which date from 1932, are used to determine the ap indices.

The ap index in turn is a mean, 3-hourly "equivalent amplitude" of magnetic activity based on K index data from a planetary network of 11 Northern and 2 Southern Hemisphere magnetic observatories between the geomagnetic latitudes of 46° and 6° by the lnstitut fur Geophysik at Göttingen, Germany; ap values are given in units of 2 nT.

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values*	Number of storm events when Kp level was met; (number of storm days)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, High Frequency (HF) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, includin g a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp = 7	200 per cycle (130 days per cycle)

Scale	Descriptor	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle)

* The Kp-index used to generate these messages is derived from a real-time network of observatories the report data to SWPC in near real-time. In most cases the real-time estimate of the Kp index will be a good approximation to the official Kp indices that are issued twice per month by the German GeoForschungsZentrum (GFZ) (Research Center for Geosciences).

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings

APPENDIX III

NOAA SPACE WEATHER SCALE FOR SOLAR RADIATION STORMS

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
		Solar Radiation Storms	Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on Extra-Vehicular Activity (EVA); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of High Frequency (HF) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***	10^4	3 per cycle

		Satellite operations: May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.		
S 3	**Strong**	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

*Flux levels are 5 minute averages. Flux in particles /·(sec.steradian.cm^2). Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.