Solar Storm Threat Analysis

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[Abstract] Most solar storms produce only minor disquieting affects on Earth. Typically one might expect short-term electrical power blackouts, short lived communication outages, rerouting of aircraft, loss of a few satellites and a beautiful "aurora borealis" in the nights sky from a large solar storm.

But as the intensity of a solar storm increases like a wild beast, the storm can begin to develop the capacity to create a major disaster on Earth. The difference in solar storm intensity is like the difference between being hit with a tropical rainstorm and being devastated by a Category 5 hurricane. The solar storm of 1-2 September 1859, which began with a solar flare so strong that it was subsequently named the Carrington Flare, was such a beast.

Oak Ridge National Laboratories estimated that only a solar storm just slightly stronger than the 13 March 1989 storm (Dst = 589 nT) would have the capacity to produce a cascading blackout involving the entire Northeastern sector of the United States. So the question is "What damage would a spawned geomagnetic storm like the one of 2 September 1859 (Dst = 1,760 nT) bring?" Would it simultaneously degrade and damage several unique large electrical transformers at key electrical generating stations taking down the massive power grid? Would the long lead-time required to manufacture and install replacement equipment result in major year long electrical blackouts, rolling blackouts and brownouts? How would a long-term lack of stable electricity affect advanced civilization?

This paper dissects and analyzes the various threats created by Great solar storms.

I. Introduction

A. General

SOLAR storms consist of three major components: solar flares, solar proton events (SPEs) and coronal mass ejections (CMEs). CMEs can interact with Earth's magnetic field to produce a geomagnetic storm. Not all solar storms produce all three elements but the largest solar storms tend to. Table 1 list the arrival time sequence for solar storm elements.

Table 1. Time Sequence of Solar Storm Events[1]

Solar Flares		
	Arrival Time:	Instantaneous[†]
	Effect Duration:	1-2 hours
Solar Proton Event		
	Arrival Time:	15 minute to a few hours
	Effect Duration:	Days
Coronal Mass Ejection		
	Arrival time:	2 or 4 days
	Effect Duration:	Days

The sun undergoes a cyclical (~22 year) pattern of magnetic pole reversals observable in the frequency of sunspot activity. This pattern is comprised of two ~11 year solar cycles phases. In the first phase, the sun's magnetic poles

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[†] Arrival times are in relationship to the time when the light from a solar flare first reaches Earth. Light takes approximately 8 minutes to traverse the distance between the Sun and the Earth.

reverse polarity. In the second phase, the sun reverses the magnetic polarity again returning the poles back to its original polarity. Sunspots are the site of origin for great solar storms.

The sun spins on its axis. As seen from Earth, the average rotation period of the Sun averages 27 days.[2] Great sunspot groups can stay active for several solar revolutions creating a cyclical ~27 day pattern of solar storms.

Solar storms vary in size and impact on Earth. One of the largest solar storms in the past 450 years occurred in September 1859. *The Sun Kings* by Stuart Clark is an excellent book describing this particular solar storm, known as the Carrington flare.[2] Because our civilization has evolved into a technologically driven /technology dependant society, a solar storm of this magnitude today could produce a major global calamity. *What has changed is the level of our reliance upon sophisticated technology, and its widespread infiltration into every niche of modern society*.[3]

This analysis is primarily focused on the rare massive solar storms that occur at a rate measured in terms of decades and centuries. There is an element of danger to these great storms and without an adequate assessment, one might be caught unawares or blindsided to this very real threat.

1. Solar Flares

Solar flares are magnetically driven explosions on the surface of the sun. Approximately 8 minutes after a solar flare occurs on the surface of the sun, a powerful burst of electromagnetic radiation in the form of X-ray, extreme ultraviolet rays, gamma ray radiation and radio burst arrives at Earth. The ultraviolet rays heat the upper atmosphere which causes the outer atmospheric shell to expand. The x-rays strip electrons from the atom in the ionosphere producing a sudden increase in total electron content.

Solar flares produce satellite communications interference, radar interference, shortwave radio fades and blackout and atmospheric drag on satellite producing an unplanned change in orbit.

Scientists classify solar flares according to their brightness in the x-ray wavelength. They group flares into 3 categories (X-class, M-class and C-class). Refer to Table 2. C-class flares are very small and produce few noticeable effects on Earth. M-class flares are medium-size and can cause brief radio blackouts in the Polar Regions. X-class flares are major events that can trigger worldwide radio blackouts and radiation storms in the upper atmosphere.

Table 2. Classification of Solar Flare Intensity

Class	Peak Flux Watts/meter^2 (100-800 picometer x-rays near Earth)
M1	0.1 x 10^{-4} W/m^2
M2	0.2 x 10^{-4} W/m^2
M3	0.3 x 10^{-4} W/m^2
M4	0.4 x 10^{-4} W/m^2
M5	0.5 x 10^{-4} W/m^2
M6	0.6 x 10^{-4} W/m^2
M7	0.7 x 10^{-4} W/m^2
M8	0.8 x 10^{-4} W/m^2
M9	0.9 x 10^{-4} W/m^2

Class	Peak Flux Watts/meter^2 (100-800 picometer x-rays near Earth)
X1	1.0 x 10^{-4} W/m^2
X2	2.0 x 10^{-4} W/m^2
X3	3.0 x 10^{-4} W/m^2
X4	4.0 x 10^{-4} W/m^2
X5	5.0 x 10^{-4} W/m^2
X6	6.0 x 10^{-4} W/m^2
X7	7.0 x 10^{-4} W/m^2
X8	8.0 x 10^{-4} W/m^2
X9	9.0 x 10^{-4} W/m^2

The largest observed solar flare was the Carrington white light flare of September 1, 1859. The largest measured solar flare occurred on November 4, 2003 and was rated as an X45. Fortunately this flare only grazed Earth.

2. Solar Proton Events (SPE)

Our sun produces high-energy solar cosmic rays (protons and ions) in Solar Proton Events (SPEs). These particles generally have energies in the range of 10 MeV to 100 MeV. Very energetic SPE events are also capable of generating near-relativistic protons in the order of 20 GeV.[4] Table 3 gives the arrival time of the protons based on energy level after the solar flare first becomes visible on the Earth. In general SPEs take around an hour to reach Earth. The fastest measured SPE in recent times occurred on 20 January 2005 with an arrival time of 15 minutes.[5]

Table 3. Velocity of Proton

Energy	Velocity (speed of light)	Arrival Time
1 MeV	0.046 c	2.9 hours
10 MeV	0.145c	49 minutes
100 MeV	0.429 c	11.1 minutes
1 GeV	0.875 c	1.2 minutes

Solar proton events produce satellite disorientation, spacecraft electronics damage, spacecraft solar panel degradation, extreme radiation hazard to astronauts, launch payload failure, high altitude aircraft radiation, shortwave radio fades and disruption in polar regions, ozone layer depletion, cardiac arrest, dementia and cancer.

High-energy protons in SPEs produce ultraviolet auroras, invisible to the human eye, when they collide with Earth's atmosphere. These reactions produce NO_x byproducts that eventually settle on the planets surface. The nitrates from large SPEs are detectable in the ice cores. Analysis of nitrate spikes in polar and Greenland ice cores show 154 large SPE (>30 MeV omni-directional fluence > 0.8 x 10^9 cm^{-2}) occurred during the past 450 years (1561-1992).[6] The largest spike was the Carrington event (September 1859) that produced an omni-directional solar proton fluence of 2.0 x 10^{10} cm^{-2}. On September 1, 1859, Richard Carrington observed a very intense white light flare on the surface of the sun from 11:18 to 11:23 a.m. GMT. Later he traveled to the Kew Observatory where magnetic recordings showed that the earth's magnetic field had recoiled as if struck by a magnetic fist at exactly the same time as Carrington saw the white light flare. The abrupt part of the disturbance had lasted just three minutes but it had then taken the next seven minutes to recover and die back down.[2] This observation shows that a massive SPE can also produce a short-lived major magnetic spike.

The mass of the CME seems to be the most dominant characteristic for producing SPE events. The larger the CME, the higher the probability a SPE event will occur. Large SPE events have a 96% correlation with a follow-on CME event.

Protons in SPEs and CMEs have energy spectrums ranging from around 10 KeV to above 20 GeV. However, solar events producing protons with energies above 1 GeV are rare. Due to geomagnetic shielding solar energetic particles with energies less than 100 MeV can only reach the Earth's atmosphere over Polar Regions where they loose their energy in collision with atoms in the atmosphere creating a cosmic ray shower of particles. If the particles have energies greater than 500 MeV, the cosmic ray shower can penetrate to the planet's surface.[7]

3. Coronal Mass Ejections (CME)

CMEs are vast clouds of seething gas, charged plasma of low to medium energy particles with imbedded magnetic field, blasted into interplanetary space from the Sun. When a CME strikes Earth, the compressed magnetic fields and plasma in their leading edge smash into the geomagnetic field like a battering ram. This causes a world-wide disturbance of Earth's magnetic field called a geomagnetic storm. This produces a temporary disturbance of the Earth's magnetosphere and an equatorial ring of currents, differential gradient and curvature drift of electrons and protons in the Near Earth region. A flood of charged particle and electrons in the ionosphere flowed from west to east, inducing powerful electrical currents in the ground that surge through natural rock. A pitch battle takes place between charged particles and magnetic fields that shake the Earth's magnetic field over a period of several hours or days. The birthplace of CMEs are often seen to originate near the site of solar flares.[3]

The severity of a geomagnetic storm depends on the orientation of Earth's magnetic field in relation to the solar storm magnetic orientation. If the particle cloud has a southward directed magnetic field it will be severe, while if northward the effects are minimized.

A CME can produce the following affects: electrostatic spacecraft charging, shifting of the Van Allen radiation belt, spacetrack errors, launch trajectory errors, spacecraft payload deployment problems, surveillance radar errors, radio propagation anomalies, compass alignment errors, electrical power blackouts, oil and gas pipeline corrosion, communication landline & equipment damage, electrical shock hazard, electrical fires, heart attacks, strokes, and workplace & traffic accidents.

B. Scope of Solar Storm Threat

Great solar storms occur approximately once per decade. Table 4 lists the great solar storms over the past 150 years. The largest solar storm ever recorded occurred on 1-2 September 1859. It was the greatest solar storm in the past 450 years. But this still leaves open the question. *Could our sun produce an even greater solar storms than the one observed in September 1859?*

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Table 4. Great Solar Storms

Date	**Solar Flare Intensity**	**Omni-Directional Solar Proton Fluence**	**Main CME Arrival Time**	**Magnetic Intensity Disturbance Storm Time (Dst) (nano-Teslas)**
1-2 September 1859	Sept 1 Carrington White Light Flare [2]	1.88×10^{10} cm^{-2} [8]	17 hours 40 minutes [9]	Sept 2 - 1,760 nT [9] (ΔH at Bombay 1,720 nT)
12 October 1859				(ΔH at Bombay 980 nT) [9]
4 February 1872				(ΔH at Bombay 1,020 nT) [9]
17-18 November 1882				(ΔH at Greenwich > 1,090 nT) [9]
30 March 1894		1.11×10^{10} cm^{-2} [8]		
31 October 1903				(ΔH at Potsdam > 950 nT) [9]
25 September 1909				(ΔH at Potsdam > 1,500 nT) [9]
13-16 May 1921				(ΔH at Potsdam 1,060 nT) [9]
7 July 1928				(ΔH at Alibag 780 nT) [9]
16 April 1938				(ΔH at Potsdam 1,900 nT) [9]
13 September 1957				Sept 13 - 427 nT [10]
11 February 1958				Feb 11 - 426 nT [10]
13 March 1989	X15			Mar 13/14 - 589 nT [10]
29 October - 5 November 2003	Oct 28 X17.2 Oct 29 X10 Nov 4 X45 [11]		19 hours	Oct 29 -353 nT [10] Oct 30 -383 nT [10] Nov 5 (missed Earth)
18-21 November 2003	Nov 18 M3.2 [9]			Nov 20/21 - 422 nT [10]

Dst is an abbreviation for the Disturbance Storm Time index that measures the strength of the magnetic storm by averaging the horizontal components of the geomagnetic field.

M-type dwarf stars called “flare stars” have been observed to create massive solar flares that can outshine their stars by over 1000 times. A two star system called “II Pegasi” produced a stellar flare in 2006 on a scale previously unimaginable for anything other than a supernova. The flare was a hundred million times more energetic than the sun’s typical solar flare, releasing the equivalent energy of 50 million trillion nuclear bombs. A solar “superflare” would cause significant death & destruction to Earth if it was directed towards our planet. But our sun doesn’t fit these conditions. Our sun is a G-type star. Nor does our sun have a companion star revolving extremely close around it at distance of only a few stellar radii.

Figure 1 attempts to answer the above question. Using proxy data derived from nitrate spikes in ice cores and data derived from moon rocks, the table compares the size of a solar storm (based on the fluence of high-energy nuclear particles) with the probability of such an event. Fluence is a measure of flux rate covering the complete timeline of a solar storm event. [As an analogy, fluence would be similar to the amount of rainfall during a rainstorm, where flux rate would be similar to the amount of rainfall per hour.] The diamond closest to the middle of the graph is the fluence from the Carrington solar storm of 1859. The data point on the lowest right portion of the graph is the largest event measured using Aluminum and Beryllium dating from moon rocks. The graph implies that solar storms with a fluence a million time greater than the Carrington solar storm are possible on a scale of approximately once every million years.

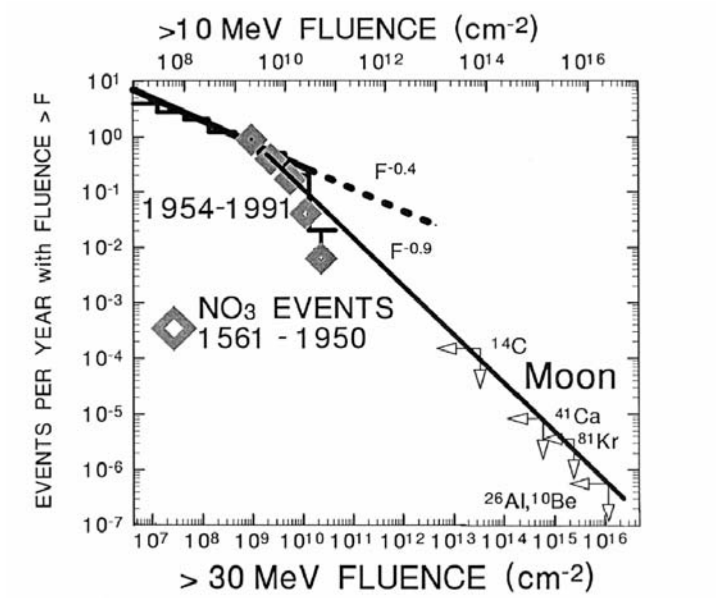

Figure 1. Estimate of the magnitude and probability of solar storms based on direct observation from satellites, nitrate spikes in Earth's ice cores and analysis of inducted radioactivity in moon rocks.[8]

SPEs in solar storms leave behind a nitrate signature in Polar and Greenland ice cores. But the burst of Galactic Cosmic Rays (GCRs) from a nearby supernova also leaves behind a nitrate spike in the ice cores. These two types of signatures are distinct in the ice cores because supernovas produce nitrate spikes of greater intensity and width (time duration). The induced radioactivity in moon rocks could be caused by SPEs or by nearby supernovas. It is my opinion that nearby supernovas predominate moon rock signatures and that the sun is fairly limited in its peak intensity range.

C. Analysis Structure

An analysis of the solar storm effects is provided below with a detailed discussion following.

- Induced Currents
    - Extensive Power Plant Outages
        - Homes
        - Transportation
        - Banking
        - Commerce and Industry
        - Other Impacts
    - Oil and Gas Pipelines
    - Long Distant Communication Lines
- Geomagnetic Field Distortion
    - Transient Distortions
    - Magnetic Pulses
- Nuclear Radiation Exposure
    - Individuals
        - Scope of Threat to Humans
    - Spacecraft Electronics
    - Air and Ground Based Electronics
- Ionospheric Reflectivity and Scintillation
    - Communications
    - Radar
    - Navigation

- Other Atmospheric Effects
  - Aurora Borealis
  - Atmospheric Envelope Expansion
  - Shifting Radiation Belts
  - Ozone Layer Depletion
  - Atmospheric Cleansing and Weather Phenomena

D. Threat Matrix

Table 5. Solar Storm Threat Matrix

Threat	Solar Flare	Solar Proton Event (SPE)	Coronal Mass Ejection (CME)
Induced Currents			X
Geomagnetic Field Distortions		X	X
Nuclear Radiation Exposure		X	X
Ionospheric Reflectivity and Scintillation	X	X	X
Other Atmospheric Effects			
- Aurora Borealis			X
- Atmospheric Envelope Expansion	X		X
- Shifting Radiation Belts			X
- Ozone Layer Depletion		X	

II. Induced Currents

When charged particles in coronal mass ejections collide with Earth, they energize auroral electrojets. These electrojets are currents of multi-million amperes or more that follow high altitude circular paths around the earth's geomagnetic poles in the magnetosphere at altitudes of about 100 kilometers.[12] These high-altitude currents induce mirror currents near the Earth's surface.[13] These mirror currents can flow into man-made conductors, like power transmission lines, pipelines, telecommunication cables and railroads tracks.[14]

A. Extensive Power Plant Outages

During a solar storm, as the CME plasma cloud collides with the planet, large transient magnetic perturbations overlay and alters the normally stable Earth's magnetic field. These magnetic perturbations are referred to as a geomagnetic storm and can affect the planet for a period of a day or two. These perturbations can induce voltage variations along the surface of the planet. Induce electric fields in the Earth create potential differences in voltage between grounding points—which causes Geomagnetic Induced Currents (GICs) to flow through transformers, power system lines, and grounding points. GICs can severely affect grounded wye-connected transformers and autotransformers through its Earth neutral connection.[12]

GICs can cause transformers to be driven into half-cycle saturation where the core of the transformer is magnetically saturate on alternate half-cycles. Only a few amperes are needed to disrupt transformer operations. A GIC level induced voltage of 1 to 2 volts per kilometer and 5 amperes in the neutral of the high-voltage windings is sufficient to drive grounded wye-connected distribution transformers into saturation in a second or less.[12] During geomagnetic storms, GIC currents as high as 184 amps have been measured in the United States in the neutral leg of transformers.[13] The largest GIC measured thus far was 270 amperes during a geomagnetic storm in Southern Sweden on April 6, 2000.

If transformer half-cycle saturation is allowed to continue, stray flux can enter the transformer structural tank members and current windings. Localized hot spots can develop quickly inside the transformers tank as temperatures rise hundreds of degrees within a few minutes.[3] Temperature spikes as high as 750° F have been measured. As transformers switches 60 times per second between being saturated and unsaturated, the normal hum of a transformer becomes a raucous, cracking whine. Regions of opposed magnetism as big as a fist in the core steel plates crash about and vibrate the 100-ton transformers which are nearly the size of a small house. This punishment can go on for hours for the duration of the geomagnetic storm. GIC induced saturation can also cause excessive gas evolution within transformers. Besides outright failure, the evidence of distress is increased gas content in transformer oil, especially those gases generated by decomposition of cellulose, vibration of the transformer tank and core, and increased noise levels of the transformers (noise level increases of 80 dB have been observed).[12] GIC transformer damage is progressive in nature. Accumulated overheating damage results in shortening transformer winding insulation lifespan eventually leading to premature failure.

In addition to problems in the transformer, half-cycle saturation causes the transformer to draw a large exciting current which has a fundamental frequency component that lags the supply voltage by 90 degrees and leads to the transformer becoming an unexpected inductive load on the system. This results in harmonic distortions and added loads due to reactive power or Volt-Ampere Reactive (VAR) demands. This results in both a reduction in the electrical system voltage and the overloading of long transmission tie-lines. In addition, harmonics can cause protective relays to operate improperly and shunt capacitor banks to overload. The conditions can lead to major power failures.[12]

When induced current flows into the electrical power grid, it has the potential of overloading the grid and causing significant damage to critical components at power plants. Solar storms can cause major electrical blackouts that can affect millions of people over a large geographic area. The electrical power grid in the US is comprised of several elements. The electricity is generated in hydroelectric dams, coal/gas/oil fired power plants and nuclear power plants. The backbone of the electrical power grid is the high voltage transmission lines operating at 230 kV, 345 kV, 500 kV and 765 kV. These transmission lines and their associated transformers serve as the long-distance heavy hauling arteries of electricity in the United States. The electricity is transferred between power generators and regional substations on very heavy supply lines suspended on 100-foot tall towers. These cables generally are three-phased systems with two hot lines and one ground. At the regional substations the voltage is converted into lower voltages from 69,000 volts to 13,800 volts. The substations feed local communities generally using telephone poles. The individual or neighborhood transformers steps the voltage down to 220 volts which supplies homes and businesses with electrical power.

The U.S. electric system includes over 6,000 generating units, more than 500,000 miles of bulk transmission lines, approximately 12,000 major substations, and innumerable lower-voltage distribution transformers. All can serve as potential GIC entry points from their respective ground connections. This enormous network is controlled regionally by more than 100 separate control centers that coordinate responsibilities jointly for the impacts upon real-time network operations.[15]

The susceptibility of electrical power grid to disruption and damage from solar storms is a function of:

<u>Latitude</u> – The closer to the magnetic poles generally means the nearer to the auroral electrojet currents, and as a result the greater the effect. The lines of magnetic latitude do not map exactly with the geographic latitude. As a result, East coast geographic mid-latitude is more vulnerable than the West coast geographic mid-latitude because the former is closer to the magnetic pole.

Strength of the Geomagnetic Storm – Greater solar storms can move the auroral electrojet currents towards the equator and intensity of the electrojets.
Earth Ground Conductivity – Regions of low conductivity, such as regions of igneous rock geology, are more susceptible. Igneous rock is common over large portions of North America. If the power plant is located over a rock stratum with low conductivity, any geomagnetic disturbance will cause a bigger change in the voltage it induces in the local ground. This will result in larger GIC current flowing into the transformers. The Earth's conductivity varies by as much as five orders of magnitude.
Orientation – Orientation of the power lines. The gradients of earth surface potential are larger in the east-west direction. As a result east-west lines are more susceptible than north-south lines.
Length – Length of transmission lines. The longer the lines the greater the vulnerability.
Power Grid Construction – The electrical DC resistance of transmission conductors and transformer windings, the transformer type and configuration, and method of station grounding can significantly affect vulnerability. Differential relay schemes on transformers are particularly susceptible to malfunction in the presence of GICs.

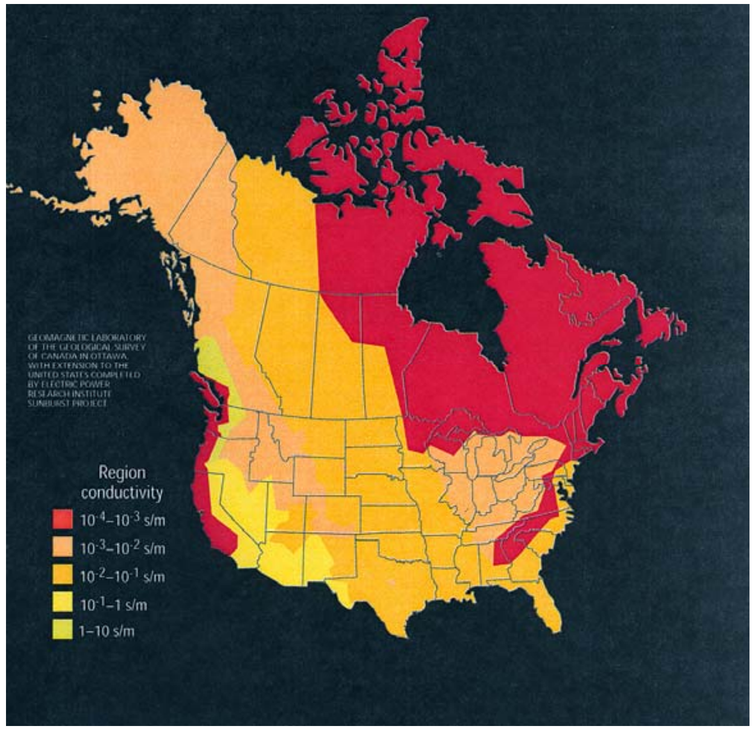

Figure 2. Earth ground resistivity based on underlying rock strata. *Conductivity measurements from the Geomagnetic Laboratory of the Geological Survey of Canada in Ottawa with Extension to the United States Completed by Electric Power Research Institute – Sunburst Project. Units – siemens per meter. (regions in red are very non-conductive).*[13]

The following geomagnetic storms damaged the electrical power grid:

August 2, 1972 – A solar storm caused a 230,000 volt transformer located at the British Columbia Hydro and Power Authority to explode.[3]

December 19, 1980 – A very expensive 735 kV transformer failed 8 days after the Great Red Aurora of 19 December at St. James Bay, Canada.

April 13, 1981 – A replacement 735 kV transformer at St. James Bay, Canada also failed the next year during another geomagnetic storm.

March 13, 1989 – At 02:45 EST on March 13, geomagnetically induced currents (GIC) inundated the transformers of the Hydro-Quebec power system and overloaded them with current. The voltage fluctuations that resulted prompted the tripping, or deactivation, of reactive power compensators at the Chibougamau, la Verendrye, Nemiscau and Albanel substations. A severe voltage drop resulted, the power lines from James Bay malfunctioned and the system collapsed. It was later determined that the power lines were substantially vulnerable due to their great length and the number of static compensators that run along their distance.[14] The Hydro Quebec outage resulted from the linked malfunction of more than 15 discrete protective-system operations. From the initial event to complete blackout, only one-and-a-half minutes elapsed—hardly enough time to assess what was occurring, let alone intervene.[15] The blackout resulted in the loss of 21,500 megawatts of electricity generation. It took nine hours to restore 83% of that electrical load.[12] The blackout affected 6 million people. The physical damage included a 1,200-ton capacitor failure at a Static VAR Compensator (SVC), overvoltage damage to two step-up transformers at the La Grande 4 generating station, surge arresters at the La Grande 2 and Churchill Falls generating stations, and to a shunt reactor at the Nemiscau substation, and damage to the SVCs themselves. The SVC thyristors at the Nemiscau substation were damaged and the SVC capacitor banks at the Albanel substation failed.[12]

March 13, 1989 – The solar storm destroyed a $12 million, generator step-up transformer owned by the Public Service Electric and Gas Company of New Jersey. The transformer was a linchpin in converting electricity from the Salem Nuclear Generating Plant. The 288.8/24-kV single-phase shell-form transformers, which are rated at 406 MVA, are connected grounded-wye. The damage to the transformers included damage to the low-voltage windings, overheating, thermal degradation of the insulation of all three phases, and conductor melting.[12] The utility asked the supplier for a replacement and was told that the order would receive top priority, but it would still take almost two years to fill.[13] Fortunately a spare transformer was made available, but it still took 6 weeks to install.

Figure 3. Generator step-up transformer owned by the Public Service Electric and Gas Company of New Jersey damaged by 13-14 March 1989 geomagnetic storm. *Images provided courtesy of Public Service Electric and Gas and Peter Balma.*

October 30, 2003 – A power grid in southern Sweden located in Malmo experienced a 20-50 minute electrical blackout affecting 50,000 customers due to a strong solar storm. The same storm caused significant transformer damage in South Africa. Over 15 transformers in South Africa were damaged, some beyond repair.

As North America has evolved into a unified power-sharing network of regions, each buying and selling a diminishing asset like a commodity, the US domestic power has become significantly more vulnerable to the effects from geomagnetic storms. Electrical power today is routed over thousands of miles of long transmission lines to keep supply and demand balanced across the electrical grid.[3] System transmission lines have become more interconnected. We are also driving power grids to operative very near their maximum capacities and this has seriously eroded reserve capacity. Continued load growth in high population centers without a corresponding growth in electricity generation capacity removes the safety margin that provides U.S. stable electrical power. Many areas have not built new transmission lines or electrical power generators for over a decade.

Devices to block GIC flow have been investigated, but they are complex and expensive to install across a large area. With current technology, protecting the network from GICs would cost several billion dollars. Instead of making these costly investments, most utility companies rely on contingency strategies for weathering severe magnetic disturbances.[15]

A solar storm can attack the power grid across many points simultaneously and can produce a multi-point failure. Large transformers which support these heavy transmission lines can cost in excess of $10 million each. Transformers of this type are custom design and build and in most cases new replacement transformers can take up to a year for manufacturing & delivery. Even if spares are readily available, it can take months to install replacements.

Large-scale blackouts can have serious economic impacts even if power is restored in a few hours. A four-hour major blackout in France was estimated to produce a 1 billion dollars loss. A major blackout in the Northeast U.S. is estimated to easily exceed several billion dollars in loss.[12] The monetary loss resulting from a year-long electrical blackout across half of the United States could easily be measured in trillions of dollars.

Electricity is essential to our industry, communications, transportation, commerce, water supply and general social welfare. Vulnerable is increasing because the country is continuing the trend of transmitting larger blocks of electrical power over longer and longer transmission lines and of operating power generation systems and transmission systems closer to their maximum power limits. Geomagnetic storms can cause severe problems for electric power systems, especially northern areas of the United States with igneous rock geology and in coastal regions.[12]

There is a singular aspect present in the very largest solar storms that have the potential for creating a global disaster, potentially knocking civilization to its knees. The very largest solar storms have the potential for simultaneously destroying key elements of the electrical power grid infrastructure. These elements are unique, expensive and have long lead times (greater than 1 year) for replacement. The Great Solar Storm of September 1859, if it were to reoccur today, has the potential of simultaneously damaging our electrical infrastructure in the East and West Coast of the United States and the power grids along the northern tier of States. This could produce an unexpected long-duration electrical power blackout affecting approximately 50% of the U.S. population. This type of massive storm would also affect high latitude and mid-latitude countries in both the northern and southern hemisphere, such as Europe, Central Asia, Russia, Canada, China, New Zealand, and South America (Southern Argentina & Chile). As the crisis evolves, partial restoration will likely occur and hard blackouts will transition to rolling blackouts and brownouts. This is the primary nature of the global threat. Herein lies the danger! Our society is technology driven and technology dependant. Without electrical power, the modern world will come crashing down.

Should this threat materialize, I also expect the crisis will quickly elevate to the level of a national imperative. All available expertise, manpower, equipment and facilities will be brought to bear to fabricate and install key damaged infrastructure elements and move the electrical power grid back into operational status. Normally one might expect a year or two to replace this equipment but under a concerted effort and mandate, I believe the damaged infrastructure could be resolved in the order of weeks rather than in years.

After the major 1989 blackout, Hydro-Quebec has invested over $1.2 billion installing transmission line series capacitors. These capacitors block GIC flow in order to prevent them from causing damage to the system.[14] Hydro-Quebec has also built shopping centre-sized sub-stations where they installed electric buffers, or valves, that convert AC power to DC and back to AC, known as "back-to-back" valves for long distant power lines. This configuration was very expensive to build and very different from the rest of North America grid, but because of its buffers and valves, is very stable and secure relative to other utility companies.[16] This investment will likely improve the survivability of that portion of the North American grid.

The following paragraphs describe the impact of a major long-term electrical power outage:

1. Homes

- Water: Individuals can only survive for a three or four days without access to clean drinking water. Without electricity to power the city water pumps and water purification plants, many individuals may lose access to clean drinking water. Lack of clean drinking water may become a critical issue during an extended power blackout lasting weeks and months.
    - Some large cities use lakes and reservoirs to hold drinking water supplies at elevated heights. These systems will be fairly resistant to extended power outages. (In New York City, approximately 95% of the total water supply is delivered to the consumer by gravity. Only about 5% of the water is regularly pumped to maintain the desired pressure.)
    - Cities that use large water pumps, water treatment plants, elevated water tanks or reservoirs located below the cities elevation may be vulnerable to extended power outages. During an electrical blackout, the pump stations that pull, move and elevate water and the water treatment plants that filter and purify the water may become inoperative due to loss of electricity. But some water plants have standby engine-generators installed to provide emergency power.
    - Many rural homes use well water or spring water. They may possess the option of powering their well pumps with portable electrical generators.
    - The Northeast Blackout of 14 August 2003 (not triggered by a solar storm) affected 50 million people in Northeastern and Midwestern United States and Ontario, Canada. Many areas lost water pressure causing potential contamination of city water supplies. Cleveland, Ohio and Detroit, Michigan issued boil water orders affecting approximately 8 million people during this crisis.
- Sewage: City waste treatment facilities depend upon electricity for operations.
    - If waste treatment facilities become inoperative due to a loss of electricity, then the untreated waste stream can either flow into rivers, streams or lakes or back up into homes and businesses. If raw sewage is allowed to overflow, it can contaminate important potential drinking water supplies. Newer communities have mandated installation of check valves in sewer lines to prevent sewage from backing up into homes. But in older communities before these standards were adopted, the waste can back up into homes turning basements into cesspool.
    - Some waste treatment plants may overcome the loss of electricity and stay in operation during an extended power outage. For example, the waste treatment plant serving Akron, Ohio in the 1960's was designed to capture and store the methane released as a byproduct of the treatment process. This methane was then used to fuel electrical power generators that powered the treatment plant and large furnaces that were used to burn the solid waste during the final phase of waste processing. The methane capture process provided approximately 60% of the plants fuel needs. These systems are more robust and may provide continuous operations during this type of crisis. Other waste treatment plants may have standby engine-generators installed to provide emergency power.
    - Without water, human waste cannot be flushed down the toilet. The stench from unflushed toilets may become overpowering and force people from their homes.
    - In rural communities, many individuals have septic tank systems. These are natural self-contained waste treatment systems that require no electricity for operation. These units should operate normally during a loss of water provided individuals haul water and manually flush toilets using buckets of water.
    - During the Northeast Blackout of 14 August 2003, Cleveland, Ohio; Kingston, Ontario and New York experienced major sewage spills into waterways.
- Refrigeration: Without electricity most freezers and refrigerators will no longer operate. Food in freezers will begin to thaw out after a day or two and this food will quickly spoil. For an average family, this can be a fairly significant monetary loss.
- Lighting: Rooms without natural lighting (windows and skylights) will be dark during the day. At night the entire house will be as dark as a cave. This will limit functionality of several rooms within the home.
- Heating: Most furnaces (electric, gas and fuel oil) will be inoperative during an electrical power outage. Gas and fuel oil furnaces will not work because electronic ignition systems, thermostats and blower motors all require electricity for operations. In the winter, the lack of heat can make it difficult to stay warm and to keep sufficient heat within the house to prevent water pipes from freezing.

- Cooling: Most air conditioners require electrical power to operate. In the hot humid summer, the lack of air conditioning and fans can make it difficult to stay cool and to exhaust the humidity from the house.
- Cooking: Most ranges and ovens will be inoperative during an electrical power outage. This includes many new gas ranges. Most new gas ranges currently available employ one of 3 basic gas ignition systems; pilot ignition, hot surface ignition system, or a spark ignition system. All three systems require electricity for operations. Without ranges and ovens, cooking meals and boiling water due to boil water orders and advisories will be difficult.

2. Transportation

Automobiles, buses and trucking will be significantly affected by an extended electrical power outage. Stoplights will stop functioning. At major intersections the loss of stoplights will lead to major gridlock.[‡] Lack of street lights will produce darkened roadways and intersections. Gasoline pumps in service stations are driven by electricity. Without electrical power, gasoline and diesel fuel will not be available to motorist and truckers. Generally the majority of service stations do not have emergency generators.

Airlines can be significantly affected by an extended major electrical power outage compounded by other solar storm effects. Without their navigational radars, no flights could land or takeoff until electrical power is restored. A blackout will disrupt the airline ticketing system. It can affect crash alarm/sirens and rescue and firefighting emergency response. Lack of electrical power can also affect Navaid, visual aids, runway lighting, ARFF station door operation, TSA screening equipment, lighting, baggage loading, loading bridge operation, airport air-conditioning, and refueling operations. The solar storm can also jam air control radio frequencies between the aircraft and ground control. Most airports are equipped with large emergency generator systems that can provide functionality to some of the critical systems.

Railway train and subway systems can be affected by inducted current from the solar storm. The tracks are long metal conductors that can pick up large inducted currents. The inducted currents can bleed over into control systems and signaling systems producing damage to equipment. In the past, induced currents were sufficient to turn the railroad signals red and to ignite fires in railroad control stations. Metro and subway systems are driven directly from electrical power. They will become inoperative during an electrical blackout stranding passengers.

3. Banking

A major electrical blackout can produce a loss of access to funds. Credit card processing, bank transactions, ATM withdrawals, check validation, payroll disbursement and even cash registers are dependant on the availability of electrical power. This problem can be compounded by the loss of key satellites that form part of the conduit for transmitting financial data.

4. Commerce and Industry

Commerce and industry will be plagued by the same problems impacting homes during a major electrical power blackout including potential interruption of water, sewage, lighting, heating and air conditioning. Add to this list other problems associated with electrical outages such as banking, computers and networks, transportation, shipping and receiving, payroll, and employee absenteeism.

Beginning in the 1960s, engineers and architects began sealing off building from the outdoors, constructing mechanical environments solely controlled by electric power. An electrical blackout will affect many modern buildings due to poor natural ventilation and lighting. Our commerce today is also very reliance on computers and telecommunications. Loss of this infrastructure will take a heavy toll.

[‡] I experienced the great San Fernando Valley earthquake of 9 February 1971 first hand. The earthquake knocked out power in several areas. At one major intersection, it took me over an hour to travel through it because the stoplight was dead. At the time, thousand of stoplights were dead and the police were spread very thin. The only way the logjam was cleared from that intersection was when private individuals went out into the street and began directing traffic. Many emergency vehicles were tied up in these traffic jams unable to respond to true emergencies.

5. Other Impacts

At the onset of an electrical blackout, people will be trapped in elevators, in underground mines, on roller coasters (some dangling from rides in midair), and inside commuter trains. (Some of these commuters will need to be evacuated from trains stopped in tunnels and between stations. It can take more than 2 hours for transit workers and emergency personnel to reach some of these trains. Those stranded in tunnels may be in pitch blackness and very afraid.)

At the onset of an electrical blackout, most individuals will want to return home before nightfall. In general, commuter trains and subways will be down. Automobile traffic in cities will be gridlocked due to inoperative traffic lights. Tunnels will close down to traffic. Ferries, buses and taxis will continue to run but expect erratic service, very long lines, crowds and chaos. In large cities, many commuters will simply walk home with some traveling over 160 city blocks.

Most individuals will be keenly interested in the extent of the outage, the cause of the outage (natural or terrorist) and a prognosis of when power will be restored. At the onset of the blackout, almost all of the FM radio stations will be initially knocked off the air. Many of these stations will return over the next hour as emergency backup generators kick in. Portable radios and car radios are key in communicating an early assessment of the blackout. Laptop computers with dial-up connections will generally continue to operate in an electrical blackout at least until their computer batteries drain down. Amateur radio will play a critical role in transmitting emergency communications.

At the onset of the blackout, many home improvement stores (e.g. Home-Depot and Lowe's) will continue to remain open because they have some flexibility in powering limited store operations using portable emergency generators. These stores can provide much needed supplies such as flashlights, batteries, portable power generators, etc. Some restaurants will remain open because gas powered brick ovens, gas ranges and fryers will not be affected by the outage.

At clogged intersections, private individuals will step forward and direct traffic to relieve the congestion. In some cases, passing police officers will distribute fluorescent jackets to these noble individuals. Drivers and pedestrians will generally follow the instructions from them even though they are not traffic police officers.

Even if cell phone service is not physically disrupted, the heavy increase in traffic can quickly overload circuits. Text messaging appears to continue to work on overloaded cell phone networks during the onset of a power outage. Mobile phone towers only have emergency backup power for a few hours and then cell phone traffic will cease.

Landline telephones run off of the small DC current that the phone company sends through the lines. But modern phones have so many gadgets that most need a separate AC adapter to run them. Unfortunately many modern phones are so poorly designed that they cannot operate at all when there is no AC current. For example, most household portable phones are useless without power to their base set.

Tall buildings will be particularly vulnerable to the effects of an electrical blackout. Elevators will not work. The lack of natural lighting in hallways and stairwells will make them pitch black. Even stairwells equipped with emergency lighting will go dark after about an hour as the batteries will drain down. Climbing stairs in the dark is very risky. The water tank on the roof will quickly empty and not be refilled because the buildings water pumps will be down. As a result, individuals will be unable to flush toilets. The air conditioner will be inoperative. Climbing long flights of stairs will be strenuous and hauling supplies of food and water back to rooms or apartments will be hard work. The buildings will be more susceptible to fire hazards because automatic fire-suppression sprinklers will no longer have available water.

An electrical blackout will produce many displaced individuals. Individuals will be stranded in airports, train and subway systems (relatives may drive into clogged cities in an attempt to pick up their loved ones). Many stranded travelers will be forced to sleep in hotel lobbies, airport terminals or out in the streets in parks or at the steps of public buildings turning them into bivouac areas.

Elderly community members and those requiring electrical medical equipment (life support systems) are more severely impacted by a power blackout than the younger population. Hospitals will have limited emergency power, often not providing air conditioning.

Electronic security may lock up due to loss of electricity. This can affect electronic gates in parking garages, card keyed doors, turnpike and toll bridge gates and for most individuals their garage door openers. These devices will need to be manually operated.

As the days pass, many workers will find it difficult to go to work because power will be out in their homes, gasoline stations will be closed, and schools and child care centers will be shut.

B. Oil and Gas Pipelines

Geomagnetic induced currents affect oil and gas pipelines. In pipelines, GIC and the associated pipe-to-soil voltages can increase the rate of corrosion in pipelines especially in high latitude regions. Damage resulting from corrosion is cumulative in nature and can eventually lead to pipeline integrity failures and major fuel leaks. As an example, GIC reaching 57 amps was measured in a Finnish natural gas pipeline in November 1998. Solar storms may have had a hand in the gas pipeline rupture and explosion on 4 June 1989 that demolished part of the Trans-Siberian Railway, engulfing two passenger trains in flames and killing 500 people, many of these were school children heading off on a vacation to the Urals.[3]

The induce currents can also affect the flowmeters that transmit the flow rate of oil/gas in the pipeline producing false readings.

Pipelines that incorporate insulating flanges can be more vulnerable to damaging GIC currents. The flanges are meant to interrupt current flow; however, it was discovered that the flanges create an additional site where the electric potential can build up and force the current flow to ground. As a result these flanges lead to increased risk for corrosion. The length of the pipeline also adds to its vulnerability due to the increased potential for corrosion.[14]

C. Long Distant Communication Lines

Geomagnetic storms can induce current on long conductive wires used as communication cables. These cables include telegraph lines, telephone land lines and undersea cables. The induced current can damage transmission lines and produce large electrical arcs and thermal heating in equipment tied to those lines. In the past, this induced current has resulted in damaged equipment, equipment fires and individuals receiving severe electrical shock.

During the large geomagnetic storm of 28 August 1859, induced currents on telegraph lines produced the following:

> "On the evening of Aug. 28th, I had great difficulty in working the line to Richmond, Virginia. It seemed as if there was a storm at Richmond. I therefore abandoned that wire, and tried to work the northern wire, but met with the same difficulty. For five or ten minutes I would have no trouble, then the current would change, and become so weak that it could hardly be felt. It would then gradually change to a 'ground' so strong that I could not lift the magnet. The Aurora disappeared at a little after 10 o'clock, after which we had no difficulty. During the auroral display, I was calling Richmond, and had one hand on the iron plate. Happening to lean towards the sounder, which is against the wall, my forehead grazed a ground wire. Immediately I received a very severe electric shock, which stunned me for an instant. An old man who was sitting facing me, and but a few feet distant, said that he saw a spark of fire jump from my forehead to the sounder."
>
> *Observations made at Washington, D.C. by Frederick W. Royce, telegraph operator.*

> "On the night of August 28th the batteries were attached, and on breaking the circuit there were seen not only sparks (that do not appear in the normal condition of a working line) but at intervals regular streams of fire, which, had they been permitted to last more than an instant, would certainly have fused the platinum points of the key, and the helices became so hot that the hand could not be kept on them. These effects could not have produced by the batteries."
>
> *Observations made in Pittsburgh, Pennsylvania by E.W. Culgan, telegraph manager.*

In the geomagnetic storm of March 25, 1940, telephone landlines designed for 48 volts were subjected to 600 volt surges and many transmission lines were destroyed. The undersea Atlantic cable between Newfoundland and Scotland saw voltages up to 2,600 volts.[*The New York Times & The Washington Post*]

New forms of cables (e.g. coaxial cables, fiber optic cables) have replaced many earlier forms of communication cables. This has allowed the bandwidth of communication systems to increase but many long cables now require repeater amplifiers along their length. These amplifiers compensate for the loss of signal strength over distance and are connected in series with the center conductor of the cable. Amplifiers are powered by a direct current supplied from terminal stations at either ends of the cable. The varying magnetic field that occurs during a geomagnetic storm induces a voltage into the center of the coaxial cable increasing or decreasing the voltage coming from the cable power supply. The induced voltage experienced during a geomagnetic storm can produce an overload of electricity on the cable system and, in turn, cause power supply failure knocking the repeaters off-line.[14] For example, the solar storm that occurred on 2 August 1972 produced a voltage surge of 60 volts on AT&T's coaxial telephone cables between Chicago and Nebraska.[3]

Submarine cables now use fiber optical cables to carry communication signals; however, there is still a long metallic conductor along the length of the cable that carries power to the repeaters and as a result is susceptible to induced currents.[14]

Geomagnetic storm induced electrical currents in long wires have caused damage to transmission lines, caused electrical arcing on telegraph equipment, caused thermal heating that resulted in electrical equipment fires, caused several telegraph operators to receive a very severe electrical shock, caused switchboards in telegraph offices to be set on fire and sending keys to melt, caused telegraph bells to automatically go off, caused very strange sounds on telephones like several sirens slowly increasing in pitch until it produced a loud screech, and caused incandescent "resistance lamps" in telegraph circuits to light.

III. Geomagnetic Field Distortion

A. Transient Distortions

A geomagnetic storm will produce erroneous course readings on magnetic compasses. This distortion will affect the full range of compasses from deep underground compasses used to guide the drills that find and recover oil; to boy scouts trying to find their way out of the woods, to magnetic compasses used on ships for navigation; to attitude control systems aboard spacecraft.

Many satellites have attitude control systems that sense the direction of Earth's magnetic field to determine up from down. During magnetic storms, polarities can change abruptly, causing satellites to upend themselves.

Some submarine detection systems use the magnetic signatures of submarines as one input to their locating schemes. Geomagnetic storms can mask and distort these signals.

B. Magnetic Pulses

There is around 50 years of scientific research linking health effects and disorders to solar storms. The threat appears to be associated with the downward vertical component of the interplanetary magnetic field. This is commonly referred to as B_z. The health effects include increased myocardial infractions (heart attacks), increased cerebral vascular accidents (strokes), increased workplace and traffic accidents and adverse effects on human judgment and behavior.

A solar storm can produce two periods of magnetic anomalies. The first is associated with the high-energy protons and ions within an SPE and this strong magnetic anomaly can last a few minutes. The second anomaly occurs a a day or two later and is associated with the huge mass of low to medium energy protons and ions within the CME. This component is reflected in the geomagnetic storm which can last for a day or two.

1. Myocardial Infractions

A study by Stoupel showed periods of high geomagnetic storms correlate to increased admissions for acute myocardial infarction (AMI, or more commonly known as “heart attacks”), more cases of anterior wall myocardial infarction, higher outpatient mortality and higher hospital mortality from acute myocardial infarctions. The number of acute myocardial infarctions increase on days before and during the geomagnetic storms. The early effects are due to the SPE and the latter effects are due to the CME. Daily death rates due to heart attacks increased approximately 70% for active/stormy geomagnetic days (K indices > 40 nT) compared to quiet/unsettled geomagnetic days (K indices < 40 nT).[17]

In a study by Kuleshova et al., hospitalization for myocardial infarctions increased 2.1 times during geomagnetic storms compared to quiet periods.[18]

It appears that acute myocardial infractions are due to damage sustained from the exposure rate to strong magnetic pulses. This can be seen in a study of railroad workers exposure to high magnetic fields. In a study by Ptitsyna et al., the relationship between ultra-low frequency (0.001-10 Hz) magnetic fields and the rates of myocardial infarctions was explored by analyzing morbidity data from 45,000 Soviet railroad workers and 4,000 engine drivers on trains powered by DC current. Vertical magnetic field pulses of ~280µT (280,000 nT) were measured in the drivers compartment of EL trains and ~50 µT in EMU trains. EL drivers were found to have a two-fold increase in risk of coronary heart disease compared to EMU drivers.[19]

A study by Toboada et al. analyzed acute myocardial infarctions for 5 hospitals in the city of Havana from 1992-1999. Their analysis showed that heart attack morbidity correlated to geomagnetic storm activity with an Ap threshold level between 20-50 (near the minimum threshold for a geomagnetic storm). The interesting item in this study is that it showed a dual morbidity peak. The first peak occurred 3 days before and the second peak occurred one day after the geomagnetic storm was first detected.[20] This finding would fall in line with the first peak caused by the induced magnetic pulses from the SPE component and the second by the CME component.

2. Cerebral Vascular Accidents

A study by Stoupel showed periods of high geomagnetic storms correlate to increased cerebral vascular accidents (CVA, or more commonly known as “strokes”) and syndromes closely related to cerebrovascular disturbances such as dizziness and migraine attacks. Daily death rates due to strokes covering severe patients who either died on the way to the hospital or in the admission rooms more than doubled (an increase of 130%) for active/stormy geomagnetic days (K indices > 40 nT) compared to quiet/unsettled geomagnetic days (K indices < 40 nT).[17]

According to a study by Kuleshova et al., hospitalization for acute violation of brain blood circulation increased 1.5 times during geomagnetic storms compared to quiet periods.[18]

3. Workplace and Traffic Accidents

Geomagnetic storms may also be responsible for many workplace accidents. In one study which analyzed accidents caused by human factors in the biggest atomic station of the former USSR at Kurskaya, during the period of 1985-1989, approximately 70% of the accidents corresponded to days of geomagnetic storms. Another study found a relationship between work & traffic accidents in Germany and geomagnetic fields. In another study, human reaction time appears to be considerably retarded during geomagnetic storms.[21]

4. Adverse Effects on Human Judgment and Behavior

Geomagnetic storms appear to affect human behavior, judgments and decisions about risk. Research has documented links to depression, enhanced anxiety, sleep disturbances, altered moods mainly affecting abstract judgment especially judgment of risk, overly cautious behavior, and greater incidences of psychiatric admissions. A study by Kay found a 36.2% increase in male hospital admissions diagnosed with the depressed phase of manic-depressive illness correlated with the second week following geomagnetic storms compared to quiet periods.[22] A study by Novikova and Ryvkin found geomagnetic storm correlates to psychotic outbursts in patients in a Moscow mental institution and to reports of hallucinations.[3] Other studies showed that pilots experienced high levels of anxiety and decreased functional activity of the central nervous system resulting in a sharp decline of flying skills during geomagnetic storms.[23] A study by Kuleshova et al. showed the daily number of hospitalizations of patients with mental disorders during geomagnetic storms nearly doubled when compared to quiet period.[18]

To put a human face on this effect consider the plight of a bright young girl in Ottawa County, Ohio who witnessed first hand the effects of the Great solar storm of September 1-2, 1859.

> The Columbus, Ohio Statesman newspaper had run a short article about a sixteen year old girl 'of considerable intelligence and prepossessing appearance', who had been taken into custody by the Sheriff of Ottawa County. Her agitated state necessitated that she be moved to the lunatic asylum. The conclusion drawn from this, and no doubt her utterances, implied that she had become deranged from viewing the aurora borealis a short time ago. She was convinced that all of this spectacular auroral activity meant that the world was soon to come to an end.
>
> ***Harpers Weekly, October 8, 1859***

The geomagnetic storm signature can even be found in financial decision making reflected in stock market transactions. In an innovative study by Krivelyova et al., evidence of substantially lower returns around the world during periods of geomagnetic activity was uncovered. The small capitalization stocks being affected by geomagnetic storms more than large capitalization stocks. Small caps are held primarily by individual investors.[23]

IV. Nuclear Radiation Exposure

A. Individuals

Not all radiation is alike. Nuclear radiation (from protons, neutrons and ions) can be one of the deadliest forms. In general, the Earth's magnetic field and our atmosphere will effectively shield individuals on the planet surface from the vast majority of high-energy nuclear radiation contained in SPEs. But particles, with energies greater than 500 MeV, generate nuclear particle streams that can penetrate down to the surface. A few particles up to 20,000 MeV (20 GeV) are believed to exist in energetic SPEs.

Individual nuclear radiation exposure from SPEs is a function of several factors including:

- intensity of the SPE
- altitude
- latitude
- direct line of sight to the sun
- atmospheric moisture levels
- chance
- the proximity to magnetic pole reversals

Individuals with the greatest exposure to this type of radiation are astronauts outside the protective envelope of Earth's magnetic field and atmosphere. The radiation levels observed in the August 1972 and the October 1989 SPEs were high enough that if astronauts had been on the surface of the Moon, shielded only by their spacesuits, the radiation dose probably would have been lethal.[3] During the solar storm at the end of 1989, astronauts inside the protection afforded by the Mir station absorbed their full-year radiation dose limit in just a few hours. Astronauts report light flashes in their eyes during solar storm events. These are caused by nuclear particles that pass through the shuttle bulkhead, causing comet-like flashes or streaks in astronaut's eyes.

Individuals flying at high altitudes will experience greater exposure because there are less air molecules between the individual and the incoming particle stream and thus less protection. Individuals at high latitudes also experience added exposure because the Earth's magnetic field will deflect many of these charged particles towards the magnetic poles. Radiation is a hazard to passengers and crew in commercial jets. For this reason, international flights passing close to the magnetic poles are rerouted to non-polar routes and the jet aircraft descend to lower altitudes during solar storms.

- New types of very high altitude aircraft are being designed. The effect of nuclear radiation from SPE on personnel in High Altitude Long Endurance (HALE) aircraft/airships can be one to three orders of magnitude greater than trans-Pacific airliners. These aircraft operate at twice the altitude and their flight times are twice as long as airliners.[24]

Individuals living in cities at higher elevation, such as Denver, Colorado (elevation 5,280 feet) will experience greater exposure to nuclear radiation than individuals living in cities at sea level, such as New York City.

Water is a natural shield against high-energy particle radiation. Therefore atmospheric moisture levels can influence exposure rates. Individual in a heavy rainstorm will gain substantial shielding.

The most dangerous particle will have the highest energies and as a result will be traveling very nearly in a straight line trajectory. Therefore at night time, the exposure rate from this threat will substantially diminish.

The exposure rate to these >500 MeV particles within an energetic SPE is small. Very few individuals will be directly affected. Therefore, it is a matter of chance. It is a function of being in the wrong place at the wrong time.

One area of greater vulnerability is physical proximity to a magnetic pole reversal, such as the South Atlantic Anomaly. Radiation doses were measured on the Russian MIR space station. Each transversal through the South Atlantic Anomaly exposed astronauts to 2 millirads behind the shielding of the MIR bulkhead. The Earth's magnetic field strength has been weakening significantly during the past century. But when the magnetic field strength is viewed from the context of the past million years, in general, the field is a very weak field, much weaker than at present. As our magnetic field returns to its normal very weak state probably during the next millennium, the field will break up from a single strong magnetic dipole into many small magnetic dipoles, many with opposite polarity. Small magnetic dipoles, such as the South Atlantic Anomaly, will become the rule rather than the exception. Some of these newly formed reverse fields will be centered over large population centers in mid-latitude and equatorial regions. As the magnetic field weakens, the vulnerability to nuclear radiation exposure from SPEs will increasingly become a greater threat.

During a solar storm, a small amount of very energetic protons and ions with energy levels exceeding 500 MeV are contained in the SPE particle stream. These very energetic solar cosmic rays have the potential of creating a particle stream that travels down to the planet's surface. If an individual is at the wrong place at the wrong time, and the nuclear particle enters the human body, it can produce very damaging effects. If the particle thermalizes within the nervous system, the release of intense ionization can cause an electrical instability in the heart and result in a Sudden Cardiac Death. If the ionization cite is the brain, it can produce permanent dementia.[25] If the ionization occurs in cells, generally the cells are destroyed and the human immune system identifies and discard these cells as a normal function. But sometimes, the damage will result in a mutation, which can lead to cancer, such as leukemia. Space weather has a direct link to random death and sickness on Earth. One of the advantages that mammals have over other types of living organisms is that unborn children are fairly well protected in the embryonic sac, which is filled with fluid, mostly water. Water is an effective shield against high-energy nuclear particles. Therefore, unborn children retain a natural protection from genetic damage of this nature.

Figure 4 defines how **protons**, **heavy ions** (such as carbon ions) and **photons** (such as X-Rays) interact as they travel through a column of water. The heavy charged particles (protons & ions) are able to cut easily through objects and dissipate significant energy at a penetrated depth (referred to as Bragg peak). When the particles are slowed down at their penetrated depth (for 148 MeV protons, the Bragg peak is at approximately 140 mm [5.5 inches]), the interaction time becomes larger and the value of the energy transfer is at its maximum. Now consider the above graph as a living organism. Water is a basic chemical component in humans. At the Bragg peak, a large amount of high-energy electrons are produced that cause multiple ionization events at the end of their range in a distance that corresponds to the cross section of a deoxyribonucleic acid (DNA) molecule. This ionization produces cluster damage at the DNA level. Energetic protons, neutrons and ions have a greater biological efficiency than X-rays and Gamma Rays to induce genetic damage. X-rays can produce isolated single and double DNA strand breaks, which can be repaired by the cells rather quickly and cleanly. High-energy proton and ion radiation produces complex cluster damage to the DNA strands that are significantly less repairable. A macroscopic tumor may originate from only one transformed cell. If a single mutated cell survives, cancer may develop.

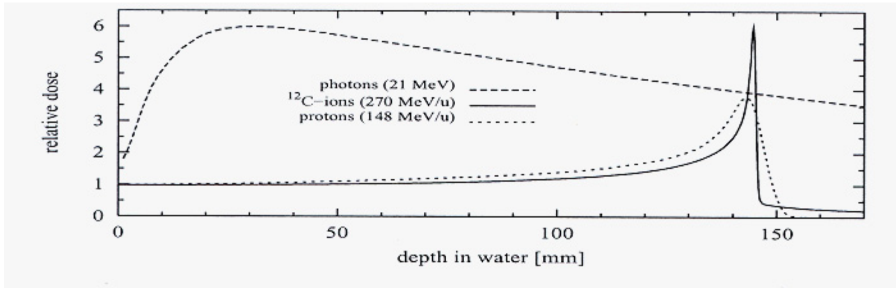

Figure 4. Proton, ion and photon radiation penetration through water.[26]

Sudden Cardiac Death (SCD, commonly referred to as cardiac arrest) is death of a cardiac origin occurring within 1 hour of preliminary symptoms. In general, this is caused by cardiac arrhythmias, electrical heart instability and heart rhythm disturbances. A study by Stoupel et al. of 788 SCDs over a 36 month period in the Baku capital city of Azerbaijan showed a correlation between SCDs and solar storms.[27] They found that days producing SCDs had an average of 8,538 imp/min daily neutron activity, compared to the daily average of 8,475 imp/min. When they looked at the days with the greatest number of SCDs (4-5), the neutron count on those days jumped even higher to 8,657 imp/min. High-energy neutrons are created from the collision of high energy protons with the Earth's atmosphere. In general, they are primarily created by GCRs. But very energetic SPEs will also produce high-energy neutrons. Therefore neutron activity can be viewed as function of both GCRs combined with very high-energy solar cosmic rays. There is another aspect of this study that is also interesting. Refer to Table 6. During quiet days, SCDs are solely influenced by Galactic Cosmic Rays (GCRs). But as weak solar storms pass near the planet, SCD rates tend to drop. CMEs even mild ones contain strong magnetic fields that can efficiently deflect incoming GCRs, shielding Earth from their effect. This phenomenon is known as the "Forbush decrease". Then as the intensity of the solar storm increases further, the quantity of the SPE high-energy particles increase, and they become a dominant factor in sudden death morbidity rates. A small number of these SPE nuclear particles are able to penetrate the Earth's magnetic field and atmosphere and reach the planet's surface. The intense ionization that occurs when one of these particles enters the human body and thermalizes is sufficient to produce an electrical pulse that short circuits the heart rhythm.

Table 6. Sudden Cardiac Death Compared to Geomagnetic Activity[27]

Geomagnetic Activity Category	SCD Distribution
Quiet (I°)	0.78
Unsettled (II°)	0.66
Active (III°)	0.64
Minor Geomagnetic Storm (IV°)	0.92

1. Scope of Threat to Humans

*What is the scope of the threat posed by **extreme** solar storms to humans?* Many medical studies deal with typical solar storms (K indices ~40 nT). The Carrington flare produced a solar storm with a Dst of 1760 nT. The solar storm effects from this type of extreme solar storm on human physiology may produce a far greater mortality figure. Two effects of solar storms pose a direct threat to human life. These are the effects caused by magnetic pulses within geomagnetic storms which are induced by SPEs and CMEs and the effects caused by high-energy nuclear particle radiation within SPEs. Many medical studies tend to smear these two effects together, which can make analysis difficult.

In order to crudely answer the above question, death records were analyzed for the year 1859, a year that produced 3 Great Solar Storms. Evidence of the first solar storm occurred when a Great Aurora became visible in many parts of the world on the night of August 28. The next solar storm occurred a few days later with the Carrington Flare & SPE on September 1 and Great Auroras on the night of September 2 & 3. The third great solar storm was detected at the Colaba Observatory in Bombay, India on October 12. The three periods covering these storms were estimated as August 26-29, September 1-4 and October 10-13. Death records from 5 counties in Kentucky (Carroll, Estill, Lawrence, Johnson and Pulaski) were analyzed.[§] These records were chosen primarily because they were readily available on-line.[28] Nineteen deaths in these counties over this combined 12 day period were 1.986 times the daily average for 1859. This indicates that magnetic pulse anomalies and nuclear SPE radiation may have been responsible for a doubling of the death rate (all causes) for that period. The 19 deaths were stratified by age categories and analyzed. The results showed this threat strongly affected the elderly, those senior citizens older than 50 years. Forty-two percent of the deaths were seniors as compared to an average of eighteen percent for seniors over the entire year of 1859.

The death rates might be a function of natural seasonal variations. In order to assess this possibility, the same county data from 1857 was analyzed. In 1857, thirteen deaths occurred during the same 12 day period. This is 1.31 times the daily average for 1857. Thus natural seasonal variation in death rates may account for ~30% of the overall trend.

Great solar storms may produce a doubling of the natural daily death rates. This effect will primarily target senior citizens older than 50 years. The magnetic pulse threat will generally take the form of acute myocardial infarction (heart attacks) and cerebral vascular accidents (strokes). Expedient access to proper medical treatment has the potential of substantially lower those deaths in future Great solar storms. The nuclear particle threat will generally take the form of sudden cardiac death (cardiac arrest).

B. Spacecraft Electronics

In the past, solar storms have caused billions of dollars of commercial satellites to malfunction and die prematurely. A Great solar storm has the power to destroy many space assets (Space Station, Space Shuttle, LEO Satellites, GEO Satellites, Off World Missions) simultaneously. In our technology driven society, satellites play an important role in communications. The loss of satellites can affect: major news wire service feeds, network television, satellite television and cable programming, nationwide radio service, weather data, cell phone service, pagers, automated teller machines, gas station credit card handling services, airline weather tracking services, earthquake monitoring network, blackberries, GPS navigation service, and critical military & airline communications. And this list grows longer every day.

Current commercial satellites are light-weight, sophisticated, built at the lowest cost using off-the-shelf electronics.[3] This current approach makes new satellite design more vulnerable to damage from solar storms.

A high-energy particle from an SPE can penetrate the wall of a satellite and deposit sufficient charge to cause an electrical upset to a circuit switch, false command, memory state change or loss.[1] As the nuclear particles collide within the spacecraft, they release electrons that build up an internal dielectric charge. This static charge can destroy circuitry on electronic boards. The particles can also change data and instructions stored in computer memory. Some of the memory damage is soft causing Single Event Upset (SEU). Generally, this anomaly can be corrected by a computer reboot. But some of the damage can be hard causing unrepairable physical damage to the junction of the microcircuit. These types of failures can be fatal.[3]

Satellites receive their operating power from large solar panels arrays. High-energy protons from SPEs and CMEs can damage the solar cells by causing the silicon atoms in the solar cell matrix substrate to violently shift position which produce crystal defects. These defects increase the resistance of the solar cells to electrical current. As a direct result, solar cell efficiency steadily decreases and solar panel power drops off.[3] A single strong solar storm can decrease lifetime of a satellite's solar panels by several years.

One critical satellite system that is very sensitive to damage from solar storms is the Attitude Control System. If the system is damaged or compromised, the satellite will become disoriented. Without accurate orientation data, the satellite will be unable to make fine adjustments to its orbit to prevent the satellite from reentering Earth's atmosphere and burning up.

[§] Only deaths with "day, month and year" listed were used in this analysis.

Another threat is differential charging. Charged particles striking different areas of a spacecraft can cause these sections of the spacecraft to be charged to different levels. Spacecraft may experience extensive surface charging as static electrical fields as high as 1,000 volts build up on the skin of the spacecraft. Electrical discharges can arc across the spacecraft components harming and potentially disabling them.

The satellite damage triggered from high-energy nuclear particles in solar storms produce a morass of delayed effects and complex phenomena that can lead to the loss of the satellite weeks or months later.[3] In one study, approximately 6,000 satellite malfunctions onboard Soviet "Kosmos" satellites over the period of 1971-1999 were analyzed to better understand the effects of solar storms. The analysis revealed there was a lag time between commencement of the geomagnetic storm [arrival of the CME] and the peak period of satellite malfunctions. For low-altitude (< 1,000 km) orbit satellites, the peak occurs approximately 5 days after the beginning of the storm. For high altitude (> 1,000 km) orbit satellites, the peak occurs approximately 2 days after the beginning of the storm.[29] This lag time is associated with the accumulating nature of the damage effects. The full extent of the damage from a massive solar storm may not be completely apparent until several weeks later.

C. Air and Ground Based Electronics

High-energy nuclear particles in a solar storm can affect aircraft avionics, passengers with cardiac pacemakers, and they can cause aircraft onboard computers to crash. A new class of high-altitude hybrid airships/dirigibles is being developed as extended loitering time, sensor/communication platforms. The higher the altitude the greater the vulnerability to the effects of electronics damage from nuclear particle radiation from SPEs.

A few high-energy nuclear particles and ions (energy levels greater than 500 MeV) within an SPE can travel all the way down to the planet's surface. This can produce equipment damage similar to the damage observed on spacecraft. The area most vulnerable are the regions of magnetic pole reversals, such as the South Atlantic Anomaly.

V. Ionospheric Reflectivity and Scintillation

Solar storms can affect radio communications, satellite communications, radars and navigation systems. On

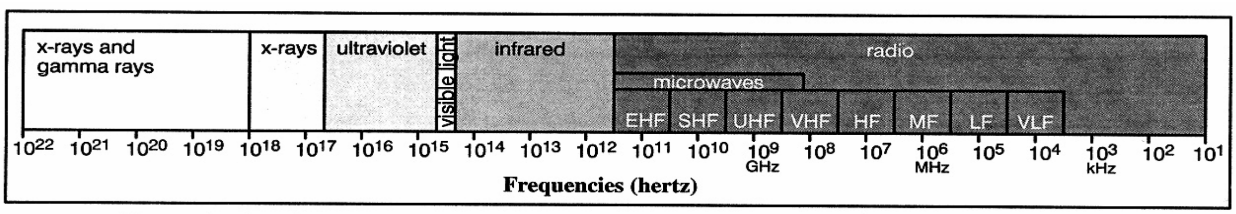

Figure 5. The electromagnetic spectrum including x-rays, visible light, and radio waves.[30]

frequencies below 30 MHz, the ionosphere generally acts as an efficient reflector, allowing radio communications to distances of many thousands of miles. Radio signals on frequencies above 30 MHz usually penetrate the ionosphere and as a result are used for ground-to-space communications.[30] Solar extreme ultraviolet and soft x-ray emissions from solar flares change the electron density and gradients in the ionosphere which profoundly affects the ionosphere reflections.

A sudden increase of x-ray radiation from a solar flare causes substantial ionization in the lower region of the ionosphere on the sunlit side of Earth. This ionization can produce sudden ionospheric disturbances of radio signals, sudden phase anomalies, sudden enhancement of signals and short wave fade. The radio disturbance can last from minutes to hours. Solar flares also produce a wide spectrum of radio noise.[30]

High-energy protons from SPEs are magnetically pulled towards the Earth's poles. The collision of these particles in the upper atmosphere creates polar cap absorption. This can impact communications from days to weeks.[30]

CMEs producing geomagnetic storms cause HF radio interference. The storms produce rapid and deep signal fading due to the ionospheric irregularities that scatter radio signals. Auroral absorption, multipathing, and non-great circle propagation effects combine to disrupt radio communications. The more intense the CME, the greater this zone of auroral irregularity moves towards the equator. These effects will last a day or two after the CME has ended.[30]

A. Communications

Solar storms can affect radio communications through ionospheric reflectivity and scintillation including:[1,12,30]

- HF radio communications (3-30 MHz)
    - effect short-wave propagation through sunlit side of Earth
    - increased absorption
    - depressed Maximum Usable Frequencies (MUF)
    - increased Lowest Usable Frequencies (LUF)
    - increased fading and flutter.
    - effect ground-to-air, ship-to-shore and amateur radio communications
- VHF propagation (30-300 MHz)
    - effect pagers and cellular phones
    - effect US Navy's MARS radio signals worldwide
    - television and FM radio stations are little affected by solar activity.
    - the high and low band in mobile voice communications for dispatching utility company line crews very susceptible to fadeout
- Satellite communications (200 MHz to several GHz)
    - increased scattering of satellite-to-ground ultra high frequency (UHF) transmissions or scintillation can seriously interfere with direct satellite communications links.
    - drastic loss in spacecraft electrical power due to inability to reposition craft.
    - erroneous positioning information from single frequency GPS
    - severe distortion of data transmissions from Geosynchronous Satellites.
    - some satellites, which employ linear polarization up to 1 GHz are affected by Faraday rotation of the plane of polarization.
    - loss of phase lock
    - Radio Frequency Interference (RFI)

B. Radar

Solar storms can also affect radar surveillance systems. Solar storms can cause range errors, elevation angle errors, azimuth angle errors and radar energy scatter due to auroral interference.

Satellites are vulnerable to collision damage from space debris. As a precaution, this debris is constantly tracked and satellite orbits are finely adjusted to avoid potential collisions. During a solar storm, Earth's atmospheric envelope expands introducing greater drag which affects the orbits of this space debris. But at the same time, radar signals become distorted and tracks are often lost.

Some military detection or early warning systems are also affected by solar activity. The over-the-horizon radar bounces signals off the ionosphere in order to monitor the launch of aircraft and missiles from long distances. During solar storms, this system can be severely hampered by radio clutter.

C. Navigation

Global Positioning System satellites operate at 1.5 GHz. GPS signals are affected when solar storm causes sudden variations in the density of the ionosphere, causing the GPS signals to scintillate. Solar storms can add small delays from the GPS satellite signals impacting accuracy. Solar storms will cause signal fades that will make it difficult to gain and maintain satellite signal locks.

LOng Range Aid to Navigation (LORAN) system operates in the 3-300 KHz range. Solar storms can black out short wave signals rendering LORAN navigation beacons useless or unreliable. Solar storms can also generate large errors in LORAN navigational system position data.

VI. Other Atmospheric Effects

A. Aurora Borealis

One of the phenomena produced by geomagnetic storms is the aurora which is visible during the nighttime hours. "Aurora Borealis" is referred to as the "Northern Lights" in the northern hemisphere and the "Southern Lights" in the southern hemisphere. Viewing an aurora even Great Auroras holds no significant danger or threat. Auroras are one of the great wonders of the natural world and the mighty power of the heavens.

Geomagnetic storms produce dazzling green and red auroras. The Earth's atmosphere is composed of primarily nitrogen and oxygen molecules. These atoms in the atmosphere absorb energy during collisions with particles imbedded in the solar storm (SPE & CME) which expands the orbit of the outer shell of electrons. When the atoms quickly return back to their unexcited stable state, the atoms release light at very discrete wavelengths. The red and green colors come from collisions with oxygen atoms. The blue and crimson colors come from collisions with nitrogen atoms.

In 1859 a cluster of extreme solar storms pounded the Earth producing a series of great aurora borealis. In Indiana, the first aurora occurred on the evening of August 28, 1859. The second (related to the Great Carrington flare) occurred on the evenings of September 2 & 3. The third struck on October 12. These great Auroras were absolutely amazing. The following is a description of the Great Aurora of August 28, 1859 as observed in Indianapolis, Indiana (located in the middle of the state at latitude 39.77 degrees North of the equator).

> <u>The Aurora</u> – The magnificent display of eternal fireworks which blazed all through Sunday night appears to have been witnessed all over the Union. At Cincinnati [Ohio] it was very similar to the [fireworks] exhibition at this place, and through the East, though we have no description of it, it must have been equally splendid, as it effectually checked all telegraph operations, a circumstance that at once indicates its intensity and demonstrates its electrical origin. There were some features of the phenomenon, as witnessed in this city, that make it unusually interesting. **1st** – It covered a much larger space of the heavens than any we ever saw, at least since 1835. **2nd** – It lasted from dark to daylight, appearing with the first approach of darkness sufficient to allow the pale light to become visible, and only disappearing as daylight gradually overpowered it. **3rd** – Instead of an arch shooting up rapid and various colored rays, its first appearance was that of luminous mist with barely perceptible rays along its southern border and moving with the rolling motion of clouds, rather than the straight darting motion usually seen in auroral phenomena. **4th** – It varied in intensity more than any we have ever seen before, twice fading nearly out, and remaining so for half hour or more and then kindling up with greater brilliance then before.
>
> When first seen about 7 1/2 o'clock, it was a barely perceivable light in the Northeast, twilight still obscuring that in the Northwest - As the darkness deepened the luminous spot grew brighter and moved to the South till a little before 8, when the light spreading from it met that coming from the Western centre (so to call it), and formed an arch about halfway between the zenith and Southern horizon, and there its advance ended, and then began instantly fading out. It retreated just as it had advanced, only more rapidly, and by ten minutes after 8 there were only the two centres, in the Northeast and the Northwest left, with a fitful gleam between them. The most singular part of this retreat was the manner in which portions of the luminous cloud broke off, and floated for some minutes far away from the main body, surrounded by deep darkness, like islands. One of them, the most beautiful, was a long bright bar in the South, which extended half way from West to East across the sky with a wide sea of darkness between it and the parent cloud, which gradually melted away, and disappeared to the Westward. We never saw such a display in any "aurora" before. At 9 o'clock the light advanced again, this time with a blood red tinge in the Eastern and Western portions, and passed clear to the South as before, but shooting up many and various colored rays, sometimes from the East, sometimes from the West, sometimes from the North, and from all parts of an irregular luminous arch that bent over the Northern horizon about twenty degrees above it. This display faded away in an hour, and at half past ten there was no light that would attract attention, more than is frequently seen in the North. But about three o'clock it blazed up with redoubled brilliance, shooting up white rays far above the zenith and making the Earth as light as a full moon behind a mist could have done. This time the rays seemed to dart up in broad masses, giving the sky the appearance of being covered with slabs of light, which were tinged with red in the zenith and rested on a broken irregular arch in the North,

> that in some places fell to the horizon, and in others rose in singular openings to thirty degrees above. In this last display the pulsations if we may so call them, of the aurora, were beautifully marked, the rays shooting up in sort of volley, many hundreds together. Broken and separate masses of luminous cloud were seen in various part of the sky during this portion of the display. It was a magnificent portion of Nature's fire works.
>
> ***The Indianapolis Daily Journal, Indianapolis, Indiana, Tuesday, August 30 1859, Vol. IX, No. 59***

This is another description of the August 28 Great Aurora from Connersville, Indiana.

> <u>The Aurora Borealis</u> – We enjoyed, with many of our fellow citizens, on last Sunday night, the sight of a beautiful electrical phenomenon. Between 7 and 8 o'clock the whole northern horizon was overspread with a soft light, which increased in size and brightness, until the whole northern section of the sky, east and west, from zenith to horizon, was all aglow. This continued until near 9 o'clock, when it gave way to varying streaks of red and white, with the blue sky for a background, the brilliant stars interspersed through all like so many diamonds; while the northeast, mantled with delicate red, appeared as if nature was blushing at her own gorgeous loveliness. While we gazed upon this beautiful phenomenon, imagination pictured the beloved emblem of our nationality, flung out upon the heavens, with its red and white stripes, floating proudly over the star-bedecked azure union.
>
> ***The Connersville Weekly Times, Connersville, Indiana, Thursday, September 1, 1859, Vol. 9, No. 51***

This is another description of the August 28 Great Aurora as seen from Philadelphia, Pennsylvania

> A most beautiful aurora borealis was visible this morning at the time of going to the press. The whole heavens were brilliantly illuminated with a searing light of many colors, crimson, and purple predominating. Streams of light ascended from all points of the horizon and met at the zenith in the form of a canopy, where they assumed the most fantastic shapes. A more beautiful sight could not be imagined.
>
> ***The Philadelphia Press, Philadelphia, Pennsylvania Thursday, Volume 3, Number 25, August 29, 1859***

Only the aurora of March 1782 compared to it.

> <u>Aurora Borealis</u> – A splendid aurora borealis, which lighten up nearly the entire heavens attracted universal attention on Sunday night. It was brightest toward morning, and reminded the beholder of the descriptions which Bayard Taylor gives of gorgeous auroral hues as seen in the high northern latitudes. In the central parts it was the brightest and on the outer edges the most beautifully tinted of any nocturnal sky light since the settlement of our city and more extensively spread through the east and west and southeast and southwest than any within the recollection of our "oldest inhabitant". It was an object of ardent gaze to many persons during all hours of the night.
>
> In March 1782, an aurora borealis overspread the whole Western Hemisphere. The light generally appears in detached places, sometimes with a constantly tremulous motion and at others more steady. It assumes all hues from a pale yellow through deep orange and violet to a blood color.
>
> ***The Indianapolis Daily Journal, Indianapolis, Indiana, Tuesday, August 30 1859, Vol. IX, No. 59***

This is a description of the 2 September 1859 Great Aurora from New Albany, Indiana (located in the extreme southern edge of the state at latitude 38.31 degrees North). The intensity of this solar storm was so great that it shifted the Aurora to the extreme south. At least one resident in New Albany believed he was observing the "Southern Lights".

> <u>Southern Lights</u> – For some three hours - commencing about midnight of Thursday the whole heavens were lighted up in the most brilliant manner. Waking up during the night we found our bedroom, though partially curtained, filled with a bright light. Not knowing whether there was a fire in the neighborhood, or it was daylight, we got up and looked at the watch, and found it to be a quarter after one - the dials on the watch (a yellow faced one) being distinctly visible within the room. When we observed it the light appeared to be generally diffused over the whole sky, but was reddest in a southerly direction, at an angle of about forty five degrees. Towards the north it appeared to be whiter. To try the brilliancy of the light

> we got a copy of the Ledger, and out of doors could distinctly read the smallest type on which it is printed. This can rarely be done by moonlight.
> Following so quickly upon the magnificent Aurora Borealis of Sunday night this phenomenon - the light appearing on the opposite side of the horizon - will doubtless attract the attention of the learned. In consequence of its appearing at so late an hour of the night, but few witnessed the splendid spectacle. It was probably what is called the Aurora Australis or Southern Light, which was first discovered by Mr. Foster, who made a voyage around the world with Capt. Cook in 1773. Capt. Wilkes makes frequent mention of having seen fine colored displays in the Antarctic regions. On Feb 9th and March 17th, 1840, there were splendid exhibitions of this phenomenon, his descriptions of which correspond in many aspects with that of last night.
>
> ***The New Albany Daily Ledger, New Albany, Indiana, Friday, September 2, 1859, Vol. XI, No. 3089***

This Great Aurora was seen in the Northern Hemisphere as far south as La Union, San Salvador at latitude 13 degrees, 18 minutes north of the equator. They described "the red light was so vivid that the roofs of the houses and the leaves of the trees appeared as if covered with blood."[2]

Sometimes the auroras blazed so brightly red that individuals and city fire departments would mistake them for large forest fires or nearby cities burning.

- August 28, 1859 Aurora: Several fire departments were called out in Washington D.C. [Evening Star]
- August 28, 1859 Aurora: Citizens of Inagua, Bahamas panicked believing a large fire was consuming their neighborhood.[2]
- September 2, 1859 Aurora: New Orleans Fire Companies in Louisiana responded to a great conflagration on the outskirts of the city, believing the city was being burned to the ground. [New Orleans Bee,]
- September 3, 1859 Aurora: Inhabitants of Kingston, Jamaica believed Cuba was being consumed by fire.[2]
- October 14, 1870 Aurora: The fire department in New Haven, Connecticut sounded the fire alarm and turned out to fight the illusion of a mass fire. [New York Times]
- February 13, 1892 Aurora: The citizens of Cincinnati, Ohio had mistaken an aurora and believed the city of Hamilton, located 25 miles to the north was on fire. [The New York Times]
- March 8, 1918 Aurora: Two officers in Atlanta, Georgia mistook an aurora and chased it thinking it was a fire. [The Atlanta Constitution]
- March 9, 1918 Aurora: The aurora had confused many into believing that the Germans had bombed London and set it ablaze. [The Washington Post].
- March 9, 1926 Aurora: The fire department at Salzburg, Austria was sent out to put out an aurora. The citizens thought the whole city was ablaze. [The New York Times]
- February 25, 1927 Aurora: The citizens of Geneva asked the fire department to extinguish the aurora. [The New York Times]
- January 25, 1938 Aurora: Fire department of Salzburg, Austria was called out to quench what residents thought was their town in flames. So many alarms were generated that the fire department dashed off in different directions. This increased the sense of panic. [The New York Times]
- January 25, 1938 Aurora: Londoners believed their entire city was ablaze. A hook and ladder brigade was summoned to Windsor Castle to put out an imaginary fire. [The London Times]
- January 25, 1938 Aurora: In Bermuda, many thought a ship was on fire at sea. Steamship agents began checking transmission to determine if an S.O.S. was given.
- September 18, 1941 Aurora: It was thought that Bremen, German was ablaze due to a large bombing raid. [The Washington Post]

B. Atmospheric Envelope Expansion

Extreme ultraviolet radiation from the solar flare can cause the Earth's upper atmosphere to heat up and expand. Auroral zone heating also contributes to this problem. Atmospheric expansion creates added drag on spacecraft causing them to slow down and slightly change orbit. This will primarily affect Low Earth Orbit (LEO) satellites operating at 400 – 1,500 miles above the surface and the Space Shuttle and Space Station typically operating at 200 – 500 miles above the surface.[3] Unless LEO satellites are boosted to higher orbits, they may fall to Earth and burn up. This phenomenon caused the premature demise of such satellites as the Solar Maximum Mission in 1990 and Skylab in 1979

C. Shifting Radiation Belts

The Van Allen Radiation Belt is a torus of energetic charged particles traveling around Earth which are held in place by Earth's magnetic field. The Van Allen Belt consists of an inner and an outer belt. The inner radiation belt extends from an altitude of 430–6,200 miles and the outer radiation belt extends from an altitude of about 8,100–40,000 miles. There is a safe region between the inner and outer belt at ~ 4,350–8,110 miles above the Earth's surface. This safe region is considered prime real estate for satellites in "middle Earth orbits" because operating in this region would experience relatively small doses of radiation and as a result the satellites would cost significantly less to build. During the October and November 2003 solar storms part of the Van Allen radiation belt was drained of electrons and then reformed much closer to the Earth within this safe region. This radiation hazard lasted for more than five weeks until the radiation was drained away and absorbed by the Earth's atmosphere.

D. Ozone Layer Depletion

A solar proton event produces significant amounts of HO_x & NO_x constituents in the mesosphere and upper stratosphere leading to extreme ozone depletion. An SPE or 14-16 July 2000 caused a middle mesospheric ozone depletion of 70%.[31] The SPE of 28 October 2003 caused a 75% decrease in ozone densities in the upper atmosphere.[32] Solar storms are the major driver in ozone depletion in the upper atmosphere. This ozone layer blocks harmful ultraviolet radiation (UV-B) from reaching the Earth’s surface. This radiation can cause skin cancer and cataracts in humans. Ozone in the upper atmosphere regenerates naturally over a period of a couple years repairing the damage wrought by a major solar storm.

As the Earth’s magnetic field continues to weaken over the next several hundred years, and other magnetic anomalies (pole reversals similar to the South Atlantic Anomaly) form; the upper atmospheric ozone layer will experience greater vulnerability to damage from SPEs.

E. Atmospheric Cleansing and Weather Phenomena

Aurora may also be associated to atmospheric cleansing allowing clearer skies immediately following the event.

> The Aurora Borealis seen from the summit of Mount Washington on the night of the 25th of August, 1853 [sic], was next morning followed by an atmosphere so clear that the spires of the churches at Portland, 95 miles distant, were distinctly seen from the summit of the mountain, and at the same time a most brilliant meteoric shower was seen from the ocean near the equator.
>
> ***Boston Transcript, August 30, 1859***

The Great Auroras may also appear to be connected to falling temperatures.

> Aurora Borealis – The Indianapolis Sentinel gives the following description of the appearance of the Borealis in that city on Saturday evening. The Lafayette and papers in other northern towns give us similar descriptions of the brilliant appearance. It was also plainly visible in this vicinity.
>
> On Saturday night we had the most gorgeous exhibition of electrical fires in the heavens, ever seen in this latitude in summer, or, indeed, that we ever saw at any time. The day had been cool and moist after the rain of Saturday and soon after sunset the heavy, banks of clouds in the west gave way before a silvery light that illuminated the northern sky, and shot its trembling arches of “dawning and of dying light” far up into the heavens converging to the zenith. Early in the evening a sheet of sparks seemed hanging in the northwest so closely resembling the effect of a large fire at a distance off, that many persons could not be persuaded that the woods were not burning in that direction. The fiery red appearance gradually died away in the west, and about 9 o’clock a far more brilliant exhibition of the same nature was to be seen in the north and east. A belt of sparks of a smoky red appearance shot up and rapidly spread over the eastern horizon until two-thirds of the sky in that direction was wrapped in the fiery shroud.

It disappeared almost as rapidly as it rose and spread, and then the fantastic play of what is well and commonly known as the Aurora Borealis or Northern Lights continued, making one feel chilly, as if we could feel the frost on our bones as we watched the pale streaks of light fading as they gleamed in their flight. At eleven o'clock and long after, the phosphorescent light shone in our windows facing to the north, by which we could read distinctly. The most brilliant exhibition, however was long after midnight, when every appearance we have attempted to describe was heightened, and a ghastly splendor overhung the earth that would defy the pen to describe or the pencil to paint.

The proverb in regard to these lights is backed by scientific authority, that they portend cold weather, but whether we are to have heavy frost before the corn is ripe or not, we are not prepared to say.

We learned late last evening that in Madison and Tipton counties, heavy frost were experienced on Sunday night week.

The Warrick Democrat, Boonville, Indiana, Tuesday, September 6, 1859, Vol. IX, No. 46

On Sunday night last, the first chill of the Fall took a crisp hold of our atmosphere. About 9 o'clock the sky presented a strange appearance, and toward the north was streaked with "beam shafts" which were variously accounted for. The most general opinion of the attracted spectators referred them to the "northern lights." The air soon after cooled so considerably that all who had been abroad with the vesture of Summer were chillingly surprised by a Winterish breeze. This strange appearance continued through the night, and has been repeated several nights since. Two hours after midnight the whole face of the .... ings, and the sight was one of the very sublimest. The Shetlanders who call these lights "the merry dancers," have had much reason to adopt that homely title, although to us they seemed too often to assume an appearance like the graceful fluttering of "the great white angel's wings," which some pious poet has somewhere or other described, and if some pious poet had not done so, the imagination were dull that could have contemplated these resplendent flickerings without some such thought!

The Erie Observer, Erie Pennsylvania, Saturday Morning, September 3, 1859

Traveling Correspondent at Iowa City September 2, 1859 – The Aurora was "up and dressed" again last night, and made fully as handsome an appearance as it did on Sunday night in Indianapolis, but I am sorry to say it keeps very bad company in this northern latitude - the frost came also, and the effect is seen today in the blighted vegetation; the extent of the damage has not yet been ascertained, but the buckwheat is killed, the potato tops and vines generally are wilted, and the little corn that wanted October suns to ripen it are surely "gone up".

The Indianapolis Daily Journal, Indianapolis, Indiana, Wednesday, September 7, 1859

VII. Conclusions

Most solar storms produce only minor disquieting affects on Earth. Typically one might expect short-term electrical power blackouts, short-lived communication outages, rerouting of aircraft, loss of a few satellites and a beautiful "aurora borealis" in the nights sky from a large solar storm.

But as the intensity of a solar storm increases it develops the capacity to create a major disaster on Earth. A Great solar storm has the potential of seriously damaging the North American electrical power grid. The resulting blackout will be focused on the northern tier of states and the East and West coast of the U.S. and throughout Canada. The damaged equipment in the power infrastructure would generally have a replacement lead time of over a year due to its uniqueness. But the scope of the outage will be so great that governments will quickly elevate its repair to the level of a *national imperative*. As a result, restoration that might normally take over a year will occur in a matter of weeks. Critical elements affected by the blackout will include water, sewage, commerce, industry, banking, transportation, communications, and in the winter, heating. Because modern society relies so heavily on sophisticated technology, a long-term blackout will have a very profound effect on the fabric of society.

Many satellites will be destroyed or severely degraded. The loss will primarily target communications. The lead time to construct and replace these assets will be measured in terms of years.

A Great solar storm (comparable in size to solar storm of September 1859) will cause an increase in the number of cases of heart attacks, strokes, and cardiac arrest. The scope of this effect will be comparable to a doubling the overall daily death rate for the length of the solar storm (~ 4 days). But expedient medical treatment for individuals affected can substantially reduce this figure.

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