Space weather: How

Could a solar flare knock out the lights? How can we ensure critical infrastructure preparedness in the face of severe space weather?

Dr Tony Phillips and **Dr Madhulika Guhathakurta** explain

ON SEPTEMBER 2, 1859, TELEGRAPH operators were shocked, literally, when they reached out to touch their teletypes. Normally docile lines were suddenly surging with dangerous levels of electricity, zapping people and setting telegraph papers on fire. Even with the batteries disconnected, the operators discovered to their amazement that they could still send messages. Powered by what? No one knew.

A glance outside before dawn would have hinted at the reason. Auroras were spreading around Earth, filling two thirds of the planet's skies with an eerie blood-red light. Northern Lights were spotted as far south as Cuba and the Bahamas. The glow was so bright that campers in the Rocky Mountains woke up in the middle of the night thinking the sun had come up. In a sense, it had. A historic solar storm was in progress.

Researchers now call it the 'Carrington Event' after astronomer Richard Carrington, who witnessed the instigating solar flare. The day before telegraph lines started crackling, Carrington sat before a projected image of the sun at his private English observatory and sketched an unusually-large group of sunspots. Suddenly, before his eyes, two brilliant beads of blinding white light appeared over the sunspots. Realising that he was witnessing something unprecedented and "being somewhat flurried by the surprise," Carrington later wrote: "I hastily ran to call someone to witness the exhibition with me. On returning within 60 seconds, I was mortified to find that it was already much changed and enfeebled." He and his witness watched the white spots contract to mere pinpoints and disappear.

> "In 1859, the Carrington Event was equal parts marvel and nuisance. In 2010, it could be a full-blown global crisis"

For the past few years, the solar cycle has been at low ebb, and geomagnetic storms have not been a problem. But the sun is waking up again. After a long absence, sunspots are now a daily occurrence and the Arctic Circle is once again alive with Aurora Borealis, as seen in this picture taken by the Expedition 11 crew aboard the International Space Station

NASA

vulnerable are we?

Only five minutes had passed, but solar physics would never be the same. Carrington had discovered the 'solar flare.'

One hundred and fifty years later, we know more or less what happened: magnetic fields looping above the sunspot criss-crossed, reconnected and unleashed an explosion more powerful than a billion atomic bombs. The blast produced a naked-eye flash of radiation and hurled a cloud of magnetised plasma (a Coronal Mass Ejection or CME) directly towards Earth. Travelling faster than 2,000 km per second, the CME crossed the 93 million mile (143 million kilometre) gulf to our planet in a mere 18 hours. When it arrived, it crashed into Earth's magnetic field with such force that compass needles on the ground below quivered visibly; charged particles rained down around the poles, causing widespread auroras; and the shaking magnetic field induced currents in telegraph wires suddenly too hot to touch.

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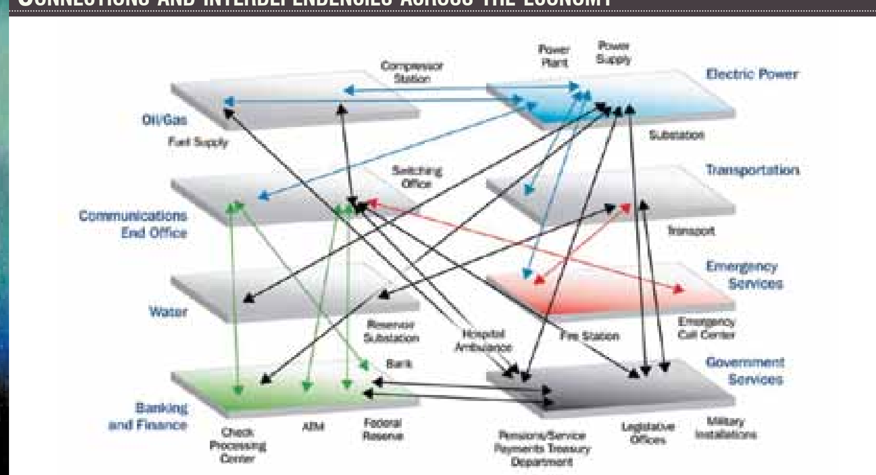
Severe space weather

"A contemporary repetition of the Carrington Event would cause extensive social and economic disruptions," warned the National Academy of Sciences in a 2008 report entitled *Severe Space Weather Events – Understanding Societal and Economic Consequences*. According to the authors, power outages would be accompanied by radio black-outs and satellite malfunctions; telecommunications, GPS navigation, banking and finance and transportation would all be affected. Some problems would correct themselves with the fading of the storm: radio and GPS transmissions could come back online fairly quickly. Other problems would be lasting: a burnt-out multi-ton transformer, for instance, can take weeks or months to repair. The total economic impact in the first year alone could reach US$2 trillion (€1.46 trillion), some 20 times greater than the costs of a Hurricane Katrina.

The problem starts with power grids. "Electric power is modern society's cornerstone technology on which virtually all other infrastructures and services depend," the report notes. If the power goes out, everything else follows.

During a geomagnetic storm, power grids can be brought down by GICs – shorthand for 'geomagnetically induced currents.' These are the same currents that coursed through telegraph lines in 1859. When the Earth's entire magnetic field is shaking, as in a geomagnetic storm, induced currents flow practically everywhere, from the upper atmosphere to the ground beneath our feet. When these currents get into power systems, they can overload circuits, trip breakers, and actually melt the windings of transformers.

Connections and interdependencies across the economy



Schematic showing the interconnected infrastructures and their qualitative dependencies and interdependencies.

source: Department of Homeland Security, National Infrastructure Protection Plan, available at wwww.dhs.gov

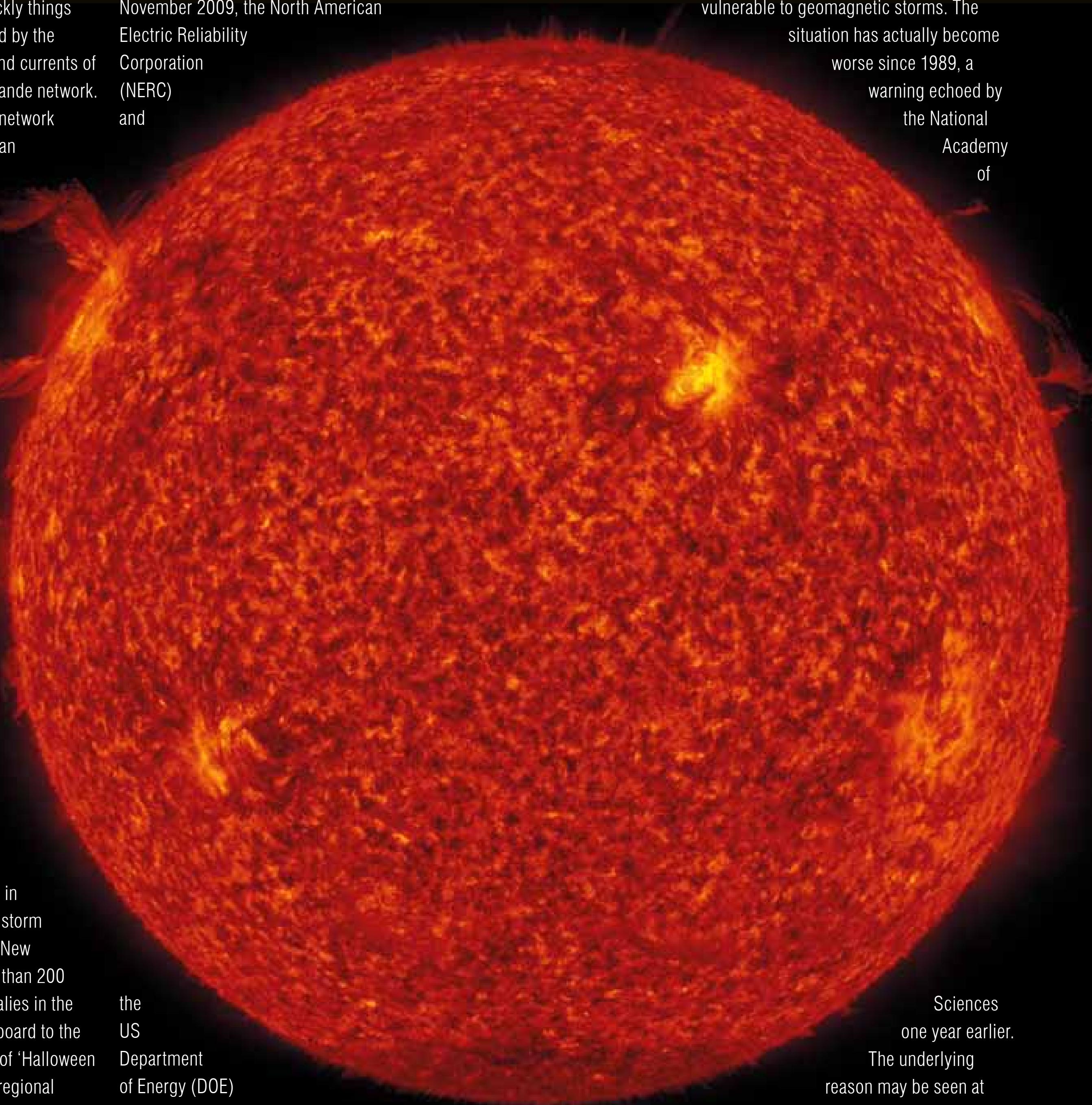
This happened in Quebec during the early morning hours of March 13, 1989. Operations on the Hydro Quebec power grid were normal at 02:44hrs (EST) when a geomagnetic storm erupted along the US/Canada border, resulting in a loss of power to more than six million people. A post-mortem analysis by the utility company gives a sense of how quickly things fell apart: "Telluric currents induced by the storm created harmonic voltages and currents of considerable intensity on the La Grande network. Voltage asymmetry on the 735-kV network reached 15 per cent. Within less than a minute, the seven La Grande network static var compensators on line tripped one after the other... With the loss of the last static var compensator, voltage dropped so drastically on the La Grande network (0.2 p.u.) that all five lines to Montreal tripped through loss of synchronism (virtual fault), and the entire network separated. The loss of 9,450 MW of generation provoked a very rapid drop in frequency at load-centre substations. The rest of the grid collapsed piece by piece in 25 seconds."

Only 92 seconds elapsed from the onset of the storm to the collapse of the grid. Indeed, rapidity is a key signature of these events. Once they begin, operators have almost no time to react.

In addition to the main black-out in Quebec, effects of the March 1989 storm included damaged transformers in New Jersey and Great Britain, and more than 200 brown-outs and other power anomalies in the USA, ranging from the eastern seaboard to the Pacific Northwest. A similar series of 'Halloween storms' in October 2003 caused a regional black-out in southern Sweden and may have damaged two transformers in South Africa.

Remarkably, these storms were about ten times less intense than the Carrington Event. In other words, it could have been – and could yet be – much worse.

Worldwide leaders and disaster management officials are beginning to take notice. In 2005, the White House itself became involved when the National Science and Technology Council's Subcommittee for Disaster Reduction identified space weather as a key hazard facing the USA. Experts from the space weather community presented a 'Space weather implementation plan' for disaster reduction to the committee in 2008. The plan is a broad-brush document setting general priorities for improving preparedness (details can be found in www.sdr.gov/185820 _ Space _ FINAL.pdf). In November 2009, the North American Electric Reliability Corporation (NERC) and the US Department of Energy (DOE) convened a workshop to discuss specific threats to the power grid. Geomagnetic storms were considered on the same footing as terrorist attacks and human pandemics. More than 110 attendees at the closed session included representatives from the US Congress, Department of Defense, the Department of Homeland Security, DOE, Department of Health and Human Services, the EMP Commission, and the Federal Energy Regulatory Commission. Representatives from each of the North American electric industries were also in attendance. Their findings have been released in a seminal report: High-Impact, Low-Frequency Event Risk to the North American Bulk Power System (hereafter, the 'NERC report').



This August, almost the entire Earth-facing side of the sun erupted in a tumult of activity
NASA/SDO/AIA

A key conclusion of the NERC report is that North American power grids are increasingly vulnerable to geomagnetic storms. The situation has actually become worse since 1989, a warning echoed by the National Academy of Sciences one year earlier. The underlying reason may be seen at a glance in this plot: Since the beginning of the Space Age the total length of high-voltage power lines criss-crossing North America has increased nearly tenfold (power grids on other continents have experienced a similar expansion). This has turned the grids into giant antennas for geomagnetically induced currents. "The scale and speed of problems that could occur (on these modern grids) have the potential to impact the power system in ways not previously experienced," according to the National Academy.

Other factors which increase the grid's vulnerability are stress and interconnectedness. The only thing growing faster than the grid is the demand for electricity; as a result, power grids are typically operated close to maximum capacity. It only takes a little nudge, easily provided by GICs, to push them over the edge. To improve the flow of power to areas of greatest need, utilities have interconnected many of their grids. On a day of record-breaking heat in Los Angeles, for instance, Angelinos might be running their air conditioners on power routed from the Pacific Northwest. This has the ironic effect of making the whole grid more vulnerable. A geomagnetic disturbance in one place can quickly spread to others along high voltage, low-resistance lines, setting the stage for a system-wide cascade failure.

Transformer damage

A large-scale black-out could last a long time, mainly owing to transformer damage. As the National Academy report notes: "These multi-ton apparatus cannot be repaired in the field and if damaged in this manner they need to be replaced with new units, which have lead times of 12 months or more."

Now for the good news: Transformer damage can be averted. All it takes is a combination of accurate forecasting and willingness on the part of utilities to take protective action when they know a storm is coming. According to the NERC report, when a strong geomagnetic storm is in the offing, utilities should:

- Postpone maintenance work and restore out-of-service lines to full operation quickly in order to maximise the capacity of the grid;
- Maintain system voltages well within the acceptable range, because voltage swings may occur;
- Adjust the flows on high voltage lines to between 40 and 90 per cent of nominal rating; and
- Reduce the loading on any generators operating at full capacity to provide reserve capacity, and take other similar measures.

Basically, the strategy is to operate the system in a conservative mode so that it can handle sudden surges of current and voltage without overload. However, no one knows if this would be adequate to survive a Carrington-class event. In such an extreme case, utility operators could choose to safeguard their transformers by actually disconnecting them from the power grids. This in itself would cause a black-out, but only temporarily. Transformers protected in this way would be available for normal operations when the storm is over.

Clearly, accurate forecasting is essential. When will a solar storm erupt? How long will it take to reach Earth? How severe will the storm be when it arrives? NOAA and NASA are working together to answer these questions.

NOAA's Space Weather Prediction Centre in Boulder, Colorado, is the USA's official forecaster of space weather events. Using data from a fleet of mostly-NASA spacecraft to monitor the sun, it issues alerts notifying utility operators and others when eruptions occur. Working together, and sometimes separately, NOAA and NASA researchers have developed sophisticated computer models to predict the 'storm track' for coronal mass ejections en route to Earth. The models are akin to National Weather Service models used to predict hurricanes and other storms on Earth – although the underlying physics is quite different.

Generally, CMEs launched from the sun take 24 to 48 hours to reach our planet. This gives forecasters time to think about what might happen when they arrive. The situation crystallises 20 to 30 minutes before impact when the CME sweeps past NASA's Advanced Composition Explorer (ACE) spacecraft. ACE sits about 1.5 million km upstream along the sun-Earth line, a lonely sentinel on the lookout for incoming storms. Sensors on ACE measure the particles and fields of the CME *in situ* and beam the information to Earth at the speed of light ahead of the approaching cloud. At that point, NOAA issues a final warning, estimating the time of arrival and severity of the storm.

> "Power grids and other critical infrastructure are increasingly vulnerable to geomagnetic storms"

Against this backdrop of approaching trouble, emergency responders can be hamstrung by suddenly-poor radio communications. During solar storms, Earth's upper atmosphere is strongly disturbed by X-rays and extreme ultraviolet photons from the sun. Energetic particles accelerated by the leading edge of the advancing CME also pepper the atmosphere, adding to already strong and variable levels of ionisation. Under these circumstances, HF propagation is dicey at best, sometimes fading to near uselessness and sometimes booming in loud and clear. It all depends on the details of the storm.

Figuring out what kind of geomagnetic storm any given CME will produce is cutting-edge research, almost as difficult as predicting when a sunspot will erupt in the first place. Both ends of the problem are among the most vexing mysteries in astro- and geophysics.

To solve a big problem, it sometimes helps to have a big group of researchers. That's where the International Living with a Star (ILWS) programme comes in. In 2002 NASA led the kick-off meeting for ILWS in Washington, DC. The ILWS was formed with the goal of stimulating and enabling a new international effort in solar-terrestrial research. ILWS provides an umbrella for forging necessary international co-ordination, co-operation, and bi-lateral and multi-lateral agency collaboration, with the goal of bringing together top thinkers from around the world to solve the underlying mysteries of space weather. At a recent meeting in Germany in July 2010, one of the authors (Madhulika Guhathakurta) handed over the chairmanship of the ILWS program to Dr Ji Wu of the Chinese Academy of Sciences. "We have many scientists and lots of fresh ideas," stated Wu. "China will be able to make important contributions in this area." China stands alongside 20 other ILWS countries actively involved in every aspect of the problem from theoretical modelling to launching new spacecraft.

There is some urgency. For the past few years, the solar cycle has been at low ebb, and geomagnetic storms have not been a problem. But the sun is waking up again. After a long absence, sunspots are now a daily occurrence and the Arctic Circle is once again alive with Northern Lights. In August 2010, a relatively minor CME hit Earth, sparking auroras as far south as Iowa in the USA. Forecasters now believe a new solar maximum will arrive around 2013. There is some disagreement about how intense it will be. Many experts, however, favour a below-average cycle with a peak sunspot number less than 100. It was just such a cycle that produced the Carrington Event of 1859.

The global economy is increasingly dependent on electricity and wireless technology. As the National Academy of Sciences concluded in 2008, future systems will have to cope: "Not only with evolving user needs and technological advances, but also with a variable space weather environment." CRJ

Authors

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