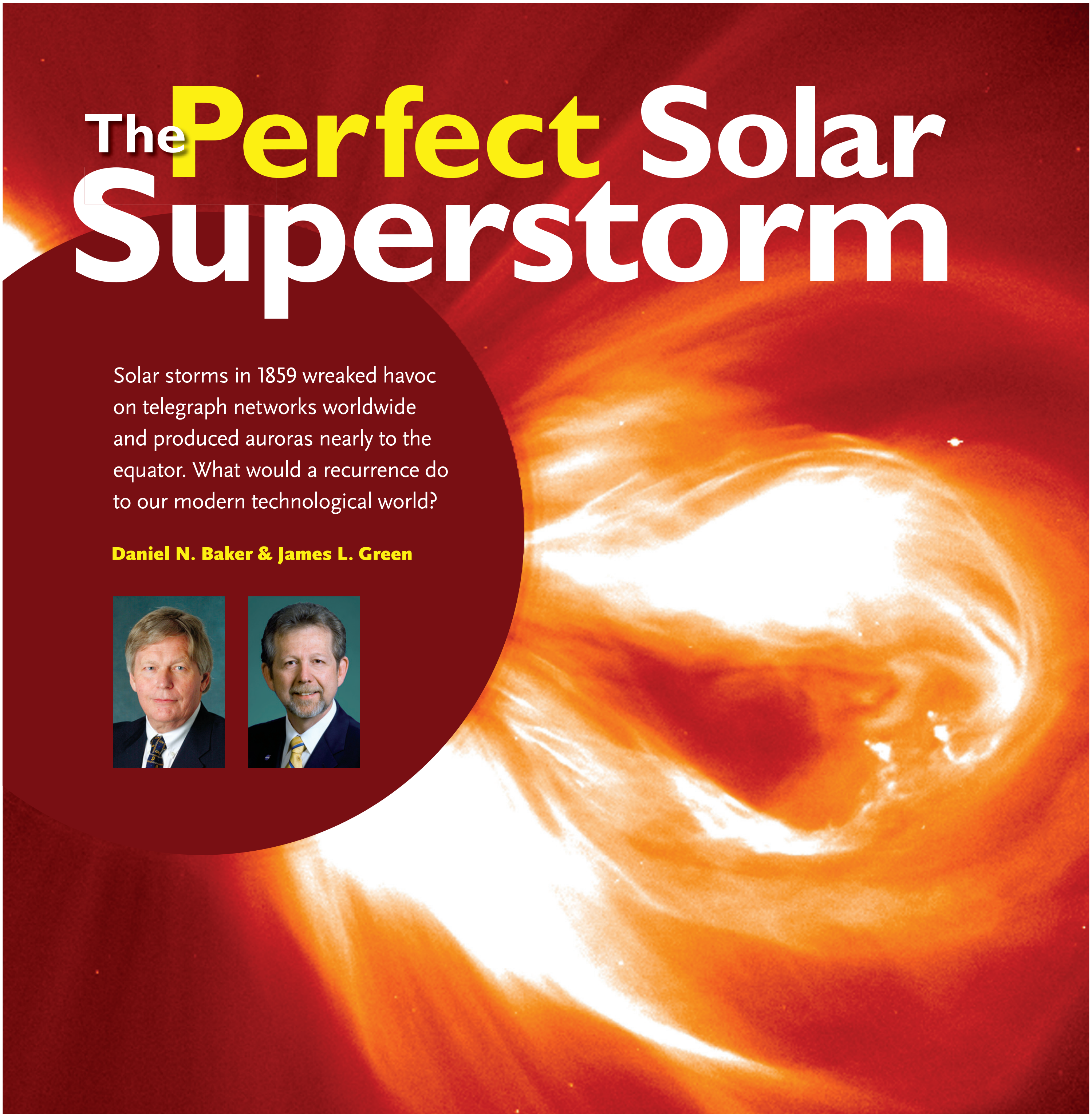


The Perfect Solar Superstorm

Solar storms in 1859 wreaked havoc on telegraph networks worldwide and produced auroras nearly to the equator. What would a recurrence do to our modern technological world?

Daniel N. Baker & James L. Green

SOHO / ESA / NASA / LASCO

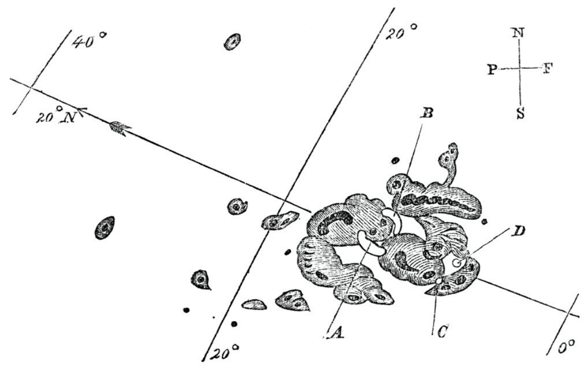
DRAMATIC AURORAL DISPLAYS were seen over nearly the entire world on the night of August 28–29, 1859. In New York City, thousands watched "the heavens . . . arrayed in a drapery more gorgeous than they have been for years." The aurora witnessed that Sunday night, *The New York Times* told its readers, "will be referred to hereafter among the events which occur but once or twice in a lifetime."

An even more spectacular aurora occurred on September 2, 1859, and displays of remarkable brilliance, color, and duration continued around the world until September 4th. Auroras were seen nearly to the equator. Even after daybreak, when the auroras were no longer visible, disturbances in Earth's magnetic field were so powerful that magnetometer traces were driven off scale. Telegraph networks around the globe experienced major disruptions and outages, with some telegraphs being completely unusable for nearly 8 hours. In several regions, operators disconnected their systems from the batteries and sent messages using only the current induced by the auroras. Earth had just experienced a one-two punch from the Sun the likes of which have not been recorded since.

Humanity was just beginning to develop a dependence on high-tech systems in 1859. The telegraph was the technological wonder of its day. There were no high-power electrical lines crisscrossing the continents, nor were there sensitive satellites orbiting Earth. There certainly was not yet a dependence on instantaneous communication and remote sensing of Earth's surface. At present, when the Sun is ramping up its activity in Solar Cycle 24, we need to ask ourselves: What would happen to our 21st-century world if a solar storm as severe as those in 1859 were to strike today?

The Sun–Earth Connection

The 1859 auroras were the visible manifestation of two intense magnetic storms that occurred near the peak of the 10th recorded sunspot cycle. On September 1st, the day before the onset of the second storm, British amateur astronomer Richard Carrington observed an outburst of "two patches of intensely bright and white light" from a large group of sunspots near the center of the Sun's disk. The outburst lasted 5 minutes and was also observed by Richard Hodgson from his home observatory near London. Carrington noted that the solar outburst was followed the next day by a geomagnetic storm, but he cautioned against inferring a causal connection between the two events.



ROYAL ASTRONOMICAL SOCIETY / © PHOTO RESEARCHERS

PRELUDE TO THE STORM **British amateur astronomer Richard Carrington sketched this enormous sunspot group on September 1, 1859. During his observations he witnessed two brilliant beads of light flare up over the sunspots, and then disappear, in a matter of 5 minutes. The next day, auroras were seen almost to the equator and telegraph systems fell silent all over the world. Carrington had observed what was probably the most intense solar flare ever recorded.**

Contemporary observers such as American astronomer Daniel Kirkwood recognized the dazzling auroral displays, magnetic disturbances, and telegraph disruptions between August 28 and September 4, 1859 as spectacular manifestations of a "mysterious connection between the solar spots and terrestrial magnetism." Several scientists had proposed such a connection earlier in the decade based on the regular observed correspondence between changes in Earth's magnetic field and the number of sunspots. By the mid-1860s, Hermann Fritz in Zürich and Elias Loomis at Yale University would furnish convincing evidence of a link between auroras and the sunspot cycle.

Although the link between solar, geomagnetic, and auroral phenomena was recognized by 1859, the nature of this link was not understood. The Carrington and Hodgson flare observations provided a vital clue. But scientists would not fully appreciate their significance until well into the 20th century. Only then would a full picture emerge of the phenomena that constitute "space weather."

Large-Scale Storms

A breakthrough came in the 1970s with the discovery of coronal mass ejections (CMEs). Scientists came to recognize that CMEs, rather than eruptive flares, are the cause of nonrecurrent geomagnetic storms. Solar flares are sudden eruptions of intense high-energy radiation from the Sun's

SOLAR ERUPTION **This image, from the Large Angle and Spectrometric Coronagraph (LASCO) aboard the Solar and Heliospheric Observatory (SOHO), shows an enormous coronal mass ejection (CME) blasting a cloud of particles into space on December 2, 2003. An occulting disk blocks the Sun. CMEs can contain 10 billion tons of gas and travel as fast as 6.7 million miles per hour. CMEs (not flares) cause the severe geomagnetic storms that affect modern society. This CME shows a preferred direction, meaning it was not aimed toward Earth.**

SOURCE: JAMES L. GREEN / NASA

AURORA REPORTS During the first 90 minutes of the September 2, 1859 solar superstorm, observers recorded auroras (red dots) nearly to the equator. Normally, auroras are only seen at high latitudes.

visible surface, producing X-rays, radio emission, and energetic particle bursts. In contrast, CMEs are enormous eruptions of plasma and magnetic fields from the corona. They can contain 10^{16} grams (10 billion tons) or more of coronal gas and travel as fast as 3,000 kilometers/second (6.7 million mph). This translates into a kinetic energy equivalent to almost 10,000 megatons of TNT.

Flares and CMEs usually occur most frequently around solar maximum and result from the release of energy stored in the Sun's magnetic field. CMEs and flares can occur independently of each other, but both are generally observed at the start of a space weather event that leads to a large magnetic storm at Earth. To drive a magnetic storm, a CME must: (1) be launched onto a trajectory that will cause it to impact Earth's magnetic field; (2) be fast (at least 1,000 km/second) and massive, thus possessing large kinetic energy; and (3) have a strong magnetic field whose orientation is opposite that of Earth's magnetic field.

The magnetic storm that began on September 2, 1859 was not caused by the highly energetic white-light flare observed by Carrington and Hodgson the previous morning. Instead, it was a fast CME launched just above and near the same giant sunspot region that produced the flare. The CME tore off an enormous section of the surrounding corona and hurled it into the solar wind.

If the ESA/NASA Solar and Heliospheric Observatory (SOHO) had been operating in 1859, its Large Angle and Spectrometric Coronagraph (LASCO) would have observed the CME perhaps 20 minutes after the flare's peak emission. The CME would have appeared as a bright "halo" of material surrounding the occulted solar disk, indicating that it was headed directly toward Earth. About 17.6 hours elapsed between the time of the flare/CME eruption on September 1st and the onset of the magnetic storm the next morning. This implies a speed of approximately 2,300 km per second (about 5 million mph), making this CME the second fastest on record. Solar physicists think the auroral storm observed on August 28th was also generated by an enormous CME that probably cleared a path in the solar wind, thereby facilitating the great speed of the September 2nd event.

Fast CMEs move much quicker than the surrounding medium, creating a shock wave that generates powerful electromagnetic forces that accelerate slow, lower-energy coronal and solar wind particles to a significant fraction

JOHN BOUDREAU

RED AURORA A red aurora lit up the sky over eastern Massachusetts on October 30, 2003. Auroras that made the sky appear "stained with blood" showed up as far south as Cuba as a result of the 1859 solar superstorm.

of the speed of light. Such large solar energetic particle (SEP) events can also include particles accelerated by flares. Traveling so rapidly, SEPs begin arriving at Earth within an hour of the flare eruption and any associated CME release. The particles are channeled along our planet's magnetic field lines into the upper atmosphere above the poles. There they enhance the ionization of the lower ionosphere over the entire polar regions. This sequence of events sometimes lasts several days.

Humans in the 1850s lacked the means to detect solar particles, and the most sophisticated technologies were unaffected by them. Thus, the September 1859 particle radiation storm went essentially unnoticed. But there is a natural record of the storm. Nitrates (NO_3^-), produced by SEP bombardment of the atmosphere above the poles, precipitate out of the atmosphere within weeks of a solar storm and are preserved in polar ice. Analysis of anomalous nitrate concentrations in ice-core samples indicates that the 1859 storm was the largest SEP event known, with flux levels several times that of the August 1972 storm — the largest solar particle event in the space era.

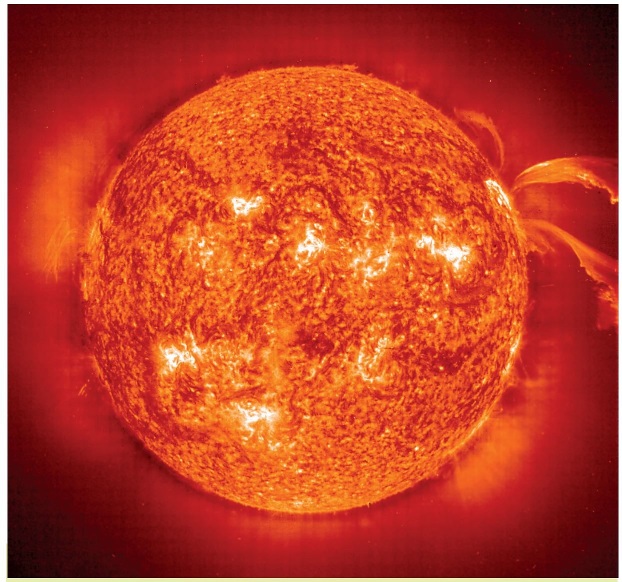
The shock wave responsible for the 1859 radiation storm hit Earth's magnetosphere at 04:50 GMT on September 2nd. It dramatically compressed Earth's magnetic field, triggering an almost instantaneous brightening of the entire auroral oval. Earth's magnetic field took several days to recover. Balfour Stewart, the director of the Kew Observatory near London, reported at that time that Earth's magnetic properties "remained in a state of considerable disturbance until September 5, and scarcely attained their normal state even on September 7 or 8."

Space Weather Effects

Contemporary observers recognized the 1859 auroral and magnetic storms as extraordinary events. But given the state of technology, the societal impact was limited to the disruptions of telegraph service, the telegraph companies' loss of income, and the associated effects on commerce and railroad traffic control.

Today, the story would be quite different. Modern society depends heavily on a variety of technologies that are vulnerable to the effects of intense geomagnetic storms and SEP events. We have turned Earth's surface, oceans, atmosphere, and near-Earth space into a tangled web of interconnected technologies. Knocking out a critical component such as electric power can ripple through society like a falling row of dominoes, triggering short- and long-term disruptions.

Strong auroral currents, which wreaked havoc with 1859 telegraph networks, can knock out modern electrical transformers and power grids. Electric power is our society's cornerstone technology on which virtually everything else depends. Although the short-term probability of a widespread blackout resulting from an extreme space weather event may be low, the consequences would



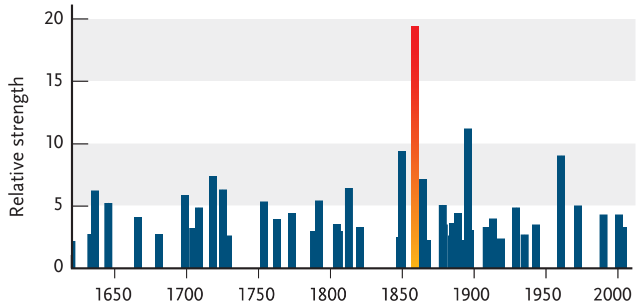
SDO / NASA / AIA SCIENCE TEAM

The Sun Ramps Up

Over an approximately 11-year period, the number of observed sunspots increases from near zero to perhaps 100 or more, and then decreases back to near zero again as the next cycle gets underway. Solar minimum of our current cycle (number 24) occurred on January 4, 2008, when a sunspot group with Cycle 24's correct magnetic-field polarity appeared at high solar latitudes. Interestingly, the Sun in the past few years has undergone the deepest minimum of activity that has been observed in more than a century (*S&T:* August 2009, page 26).

The underlying cause of a sunspot cycle remains one of the great mysteries of solar physics. While we know many details, we still have not yet developed a reliable predictive modeling capability. Scientists currently predict that Cycle 24 will peak in the summer of 2013, with a smoothed sunspot maximum of about 60 with fluctuations that may be as high as 90. Predicting the behavior of a sunspot cycle is fairly reliable once we have been in the cycle for about 3 years after sunspot minimum. Since it's still early in Cycle 24, forecasters might need to slightly revise the predicted timing and sunspot number of the next maximum.

Despite the recent modest increase in sunspot numbers and relatively weak solar flaring, this approaching maximum still appears to be one of the least-active cycles since Cycle 19, whose sunspot maximum occurred in the late 1920s. But the sunspot number is not always a reliable indicator of solar storm intensity, because the 1859 superstorm occurred during a sunspot maximum that was less than the previous 7 cycles. We must therefore wonder if this upcoming maximum will produce a series of events similar to those of the 1859–60 maximum.



POLAR SPIKE Geoscientists have identified a big spike in nitrate concentrations in polar ice dating to the 1859 solar superstorm.

be very high — its effects would cascade through other dependent systems like a space weather Katrina.

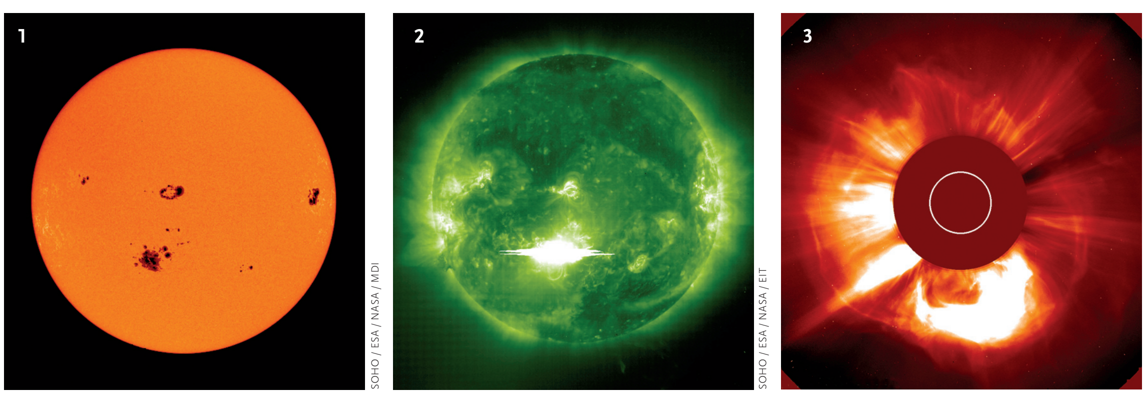
A March 13, 1989 power-grid blackout in Québec and the consequent forced power outages in the northeastern United States remain the classic example of severe space weather's impact on the electric-power industry. According to a thorough study by the Metatech Corporation, the occurrence today of an event like the May 1921 solar storm would result in large-scale blackouts affecting more than 130 million Americans and would expose more than 350 extra high-voltage (EHV) transformers to the risk of permanent damage. Because of the limited manufacturing capacity for EHV transformers in the U.S. and the rest of the world, large areas of our nation could be without electricity for *months or years,* as power companies struggle to purchase and replace damaged hardware.

A long power outage would disrupt transportation, communication, banking, medical care, financial systems, and government services. The distribution of potable water would break down because of pump failure, and we would experience the loss of perishable foods and medications because of the lack of refrigeration. The resulting loss of services for weeks, months, or years in even one region of the country would have enormous national and international repercussions.

Even less-severe storms can affect various industries. Magnetic-storm-driven ionospheric disturbances interfere with radio communications and GPS navigation signals. Radiation events can degrade or completely black out high-frequency radio communications along transpolar aviation routes, requiring aircraft to be diverted to lower latitudes and/or lower altitudes — costing airlines money and inconveniencing passengers. Spacecraft exposed to SEP events can suffer temporary anomalies, damage to critical electronics, degraded solar arrays, and blinded cameras and star trackers. Intense SEP events pose a significant radiation hazard for International Space Station astronauts during the high-latitude segment of the orbit, and energetic particles would threaten the lives of astronauts beyond the protection of Earth's magnetosphere.

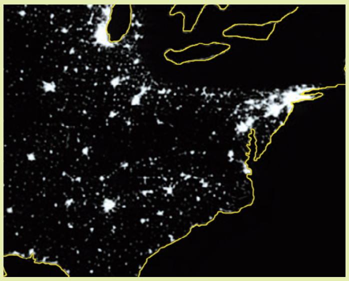
Industries have responded to space weather threats by improving procedures and technologies. Alerted to an impending geomagnetic storm by NOAA's Space Weather Prediction Center and monitoring ground currents in real-time, power-grid operators can take defensive measures. For example, they can temporarily divert power flow from the most severely affected parts of the grid to protect the entire grid against geomagnetically induced currents.

If warned of an upcoming 1859-level geomagnetic storm, operators could shut down a few EHV transformers to avoid burnouts. But that would concentrate dangerous current flows into the remaining transformers. Nobody has the authority to shut down the entire national electric grid. But even if someone did, the resulting widespread blackout



SOLAR STORM EVOLUTION *Left to right, both pages:* These SOHO images trace the evolution of the powerful October 28, 2003 solar storm, which caused satellite anomalies and power-grid disruptions in northern Europe. *1.* SOHO's Michelson Doppler Imager (MDI) captures a large sunspot group at 6:24 UT. 2. At 11:12 UT, the Extreme ultraviolet Imaging Telescope (EIT) caught an X-ray flare emanating from the sunspot group. The flare was so intense that it saturated the detector. *3.* This LASCO image, taken at 11:30 UT, shows a large CME expanding outward. *4.* This "difference" image subtracts EIT and LASCO images taken around 11:24 to 11:30 UT

How Space Weather Causes Blackouts



Auroral currents from space weather induce powerful, fluctuating direct currents (DC) in electrical power grids. These currents flow through large extra high-voltage transformers and can cause the transformers to saturate and overheat. This saturation can be severe enough to cause network-wide voltage-regulation problems, which can lead to widespread blackouts. The most intense current flows can burn out transformers in a matter of minutes. The problem can quickly spread because power grids barely recognize political borders. The North American grid links the U.S. and Canada in very important ways. When the March 13, 1989 blackout occurred in Québec, it naturally propagated throughout the entire Northeast region. It was only good luck that the disruption was stopped as effectively as it was and relatively minor effects were felt in the U.S.

WIDESPREAD BLACKOUT This artwork simulates what a satellite would have seen during the power outage of March 13, 1989. The blackout knocked out power in all of Québec for 12 hours, and affected the grid in the northeastern U.S. for a shorter time interval. An 1859-level event would cause more severe and widespread disruption to the grid.

NASA

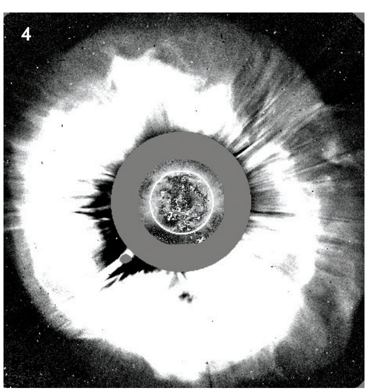
could cost tens of billions of dollars, and it could turn out to be a false alarm. According to Metatech, hardening the national grid against the effects of a severe storm would be much cheaper than a single false alarm or forced blackout.

As for other industries, space agency officials can delay a launch and satellite operators can postpone critical operations. The aerospace industry has designed satellites to operate under extreme conditions. GPS modernization through the addition of two new navigation signals and codes will help lessen space weather effects.

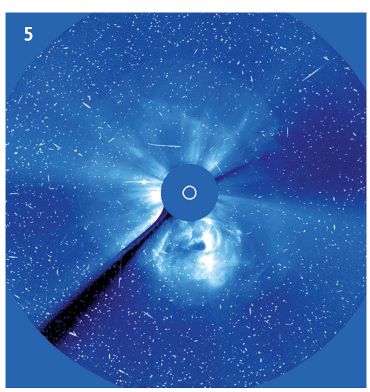
Future Vulnerabilities

Extreme space weather disturbances are low-frequency/high-consequence (LF/HC) events. Public and private institutions require different budgeting and management capabilities to deal with the collateral impacts of such events. Space weather challenges the basis for conventional policies and risk-management strategies, which normally assume constant or reliable conditions. It's difficult to understand, much less to predict, the consequences of future LF/HC events. Sustaining preparedness and planning for such events in future years is crucial. Without being unduly alarmist, we contend that policymakers must address space weather as a key LF/HC matter of vital importance to our modern society.

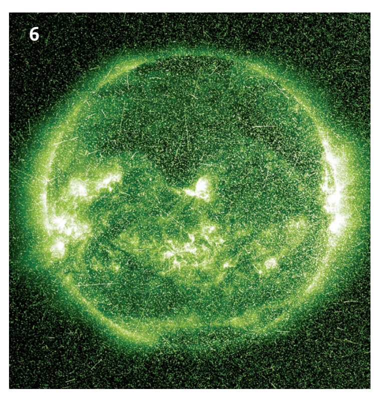
Our understanding of the vulnerabilities of modern infrastructure to severe space weather and the measures developed to mitigate those vulnerabilities are based largely on experience gained during episodes such as the geomagnetic storms of March 1989 and October–November 2003. The 1859 and 1921 superstorms suggest that such extreme events, though rare, will almost certainly occur in the future. It's sobering to recognize that a large flare and CME in November 2003 occurred on the Sun's



SOHO / ESA / NASA / EIT / LASCO

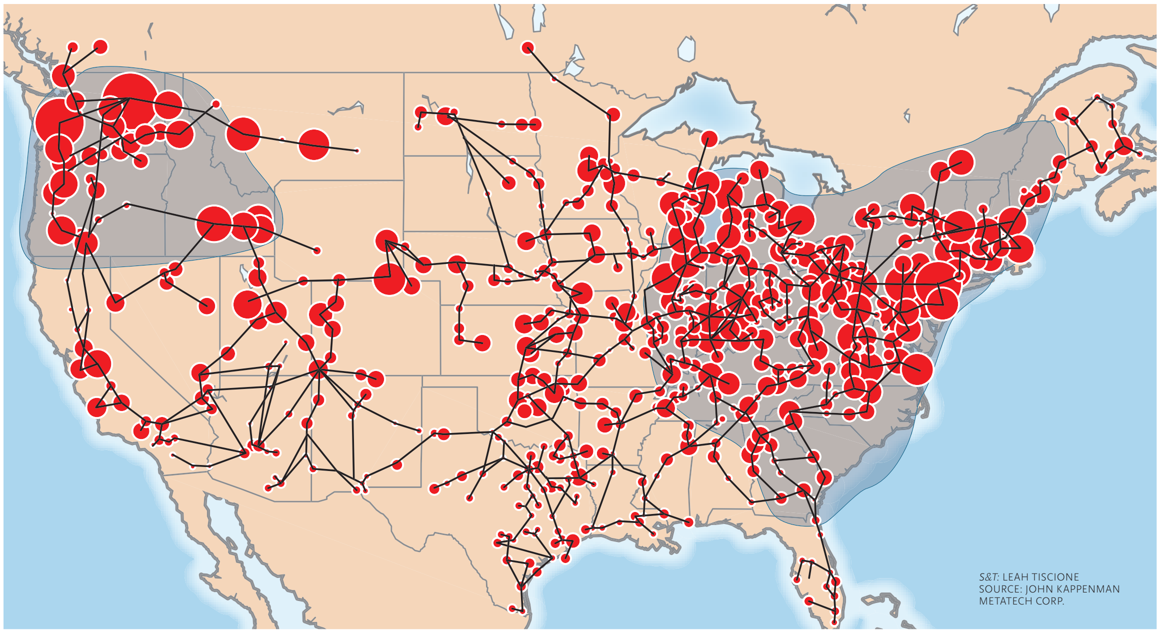


SOHO / ESA / NASA / LASCO



SOHO / ESA / NASA / EIT

from earlier images to reveal changes. This "halo" illusion (ejected material appears to be spreading in all directions), coupled with the fact that the active region was almost directly facing Earth, informed scientists that the CME was heading our way. *5.* At 12:42 UT, a shower of energetic solar protons produced the "snow" effect in this LASCO image. *6.* Later in the day, at 23:54 UT, the shower of particles was so intense that it made this EIT image look like it was in the midst of a blizzard. Combined, these six images give us a sense of what a SOHO-like spacecraft would have seen if one was operating in 1859. But the 1859 storm was considerably more powerful.



THE GRID This map is based on a study by Metatech Corporation. Dark lines show routes of extra high-voltage (EHV) transmission lines and major power substations. Geomagnetic electric currents from a solar storm will flow through these lines to major transformers, marked by red dots. The relative sizes of the dots indicate the magnitude of the current. Due to the powerful flows of current, 300 large EHV transformers would be at risk of permanent damage or failure. The electric grid and transformers in the gray shaded regions could suffer a catastrophic collapse, leaving more than 130 million people without electricity. Because of the limited manufacturing capability for these large EHV transformers, it could take *months or years* to restore power in some areas.

limb and were therefore not aimed directly at Earth. Had they occurred at a more central solar longitude, we probably would have experienced an 1859-level event. We figuratively and literally dodged a major bullet. With a new solar maximum approaching around 2013, a giant event could occur during this developing cycle.

Despite the lessons learned since 1989 and their successful application during the 2003 storms, the United States's electric power grid has become even more vulnerable in terms of both widespread blackouts and permanent equipment damage requiring long restoration times. What emerged from a recent U.S. National Academy of Sciences study is that industry experts understand well the effects of moderately severe space weather on specific technologies. In many cases they know what is required to mitigate space weather through enhanced forecasting and monitoring capabilities, new technologies, and improved operations. Limited information also emerged on the socioeconomic costs of power outages: $4–10 billion for the August 2003 blackout, which was not caused by space weather, and an estimated $1–2 trillion during the first year alone for a "severe geomagnetic storm scenario" with recovery times of 4 to 10 years. Many other nations share similar vulnerabilities.

While our recent work has organized much of what is currently known or suspected about socioeconomic impacts, it has perhaps been most successful in illuminating the scope of the myriad issues involved, and the gaps in knowledge that remain to be explored in greater depth. It's difficult to fathom how damaging an 1859-type event might be in today's world. We need to prepare better for such a possibility and help policymakers understand what can and should be done to mitigate possible effects. ✦

To read the entire National Academy of Sciences report "Severe Space Weather Events — Understanding Societal and Economic Impacts," visit www.nap.edu/openbook.php?record_id=12507&page=R1.

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