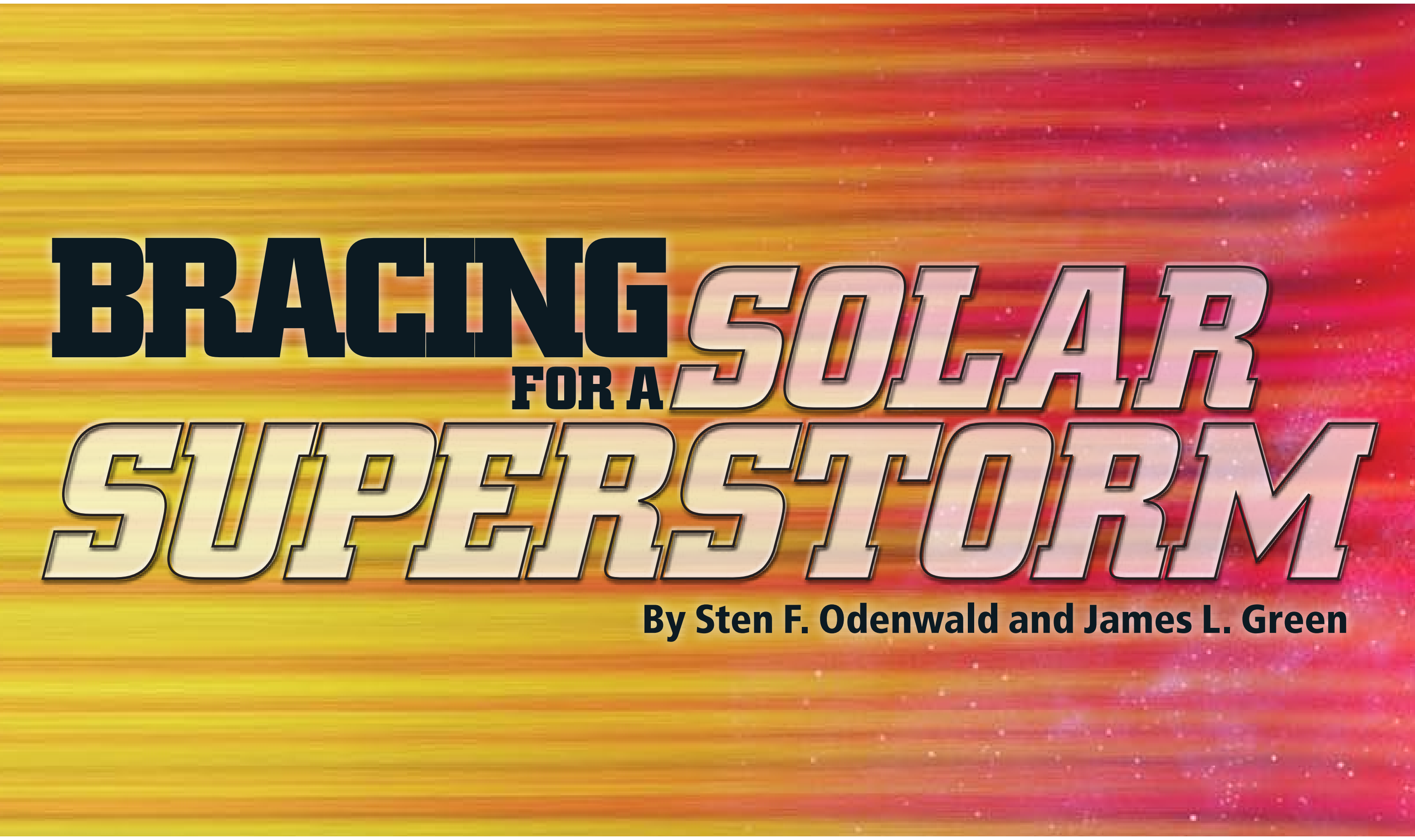


BRACING FOR A SOLAR SUPERSTORM

By Sten F. Odenwald and James L. Green

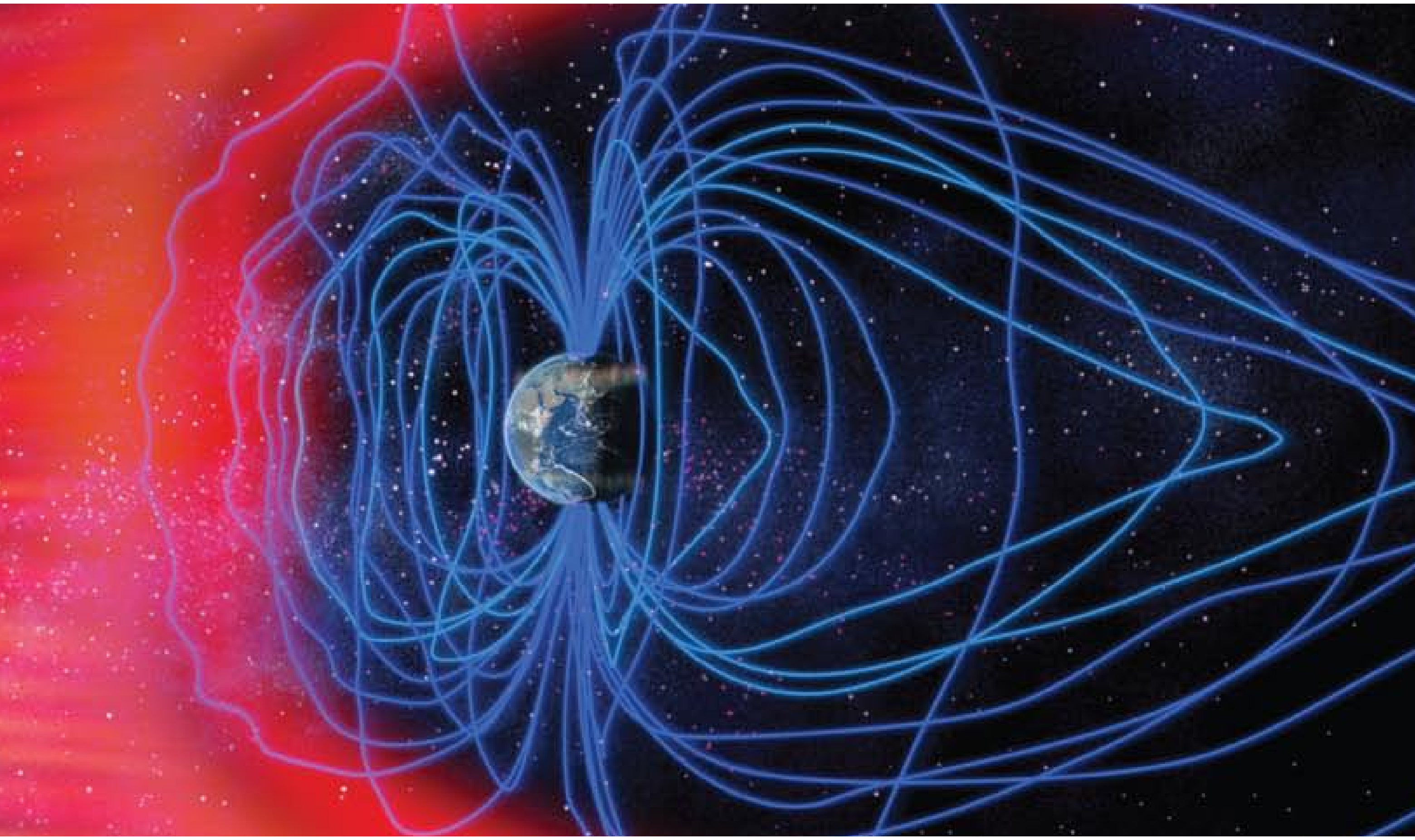
A recurrence of the 1859 solar superstorm would be a cosmic Katrina, causing billions of dollars of damage to satellites, power grids and radio communications

As night was falling across the Americas on Sunday, August 28, 1859, the phantom shapes of the auroras could already be seen overhead. From Maine to the tip of Florida, vivid curtains of light took the skies. Startled Cubans saw the auroras directly overhead; ships' logs near the equator described crimson lights reaching halfway to the zenith. Many people thought their cities had caught fire. Scientific instruments around the world, patiently recording minute changes in Earth's magnetism, suddenly shot off scale, and spurious electric currents surged into the world's telegraph systems. In Baltimore telegraph operators labored from 8 P.M. until 10 A.M. the next day to transmit a mere 400-word press report.

Just before noon the following Thursday, September 1, English astronomer Richard C. Carrington was sketching a curious group of sunspots—curious on account of the dark areas' enormous size. At 11:18 A.M. he witnessed an intense white light flash from two locations within the sunspot group. He called out in vain to anyone in the observatory to come see the brief five-minute spectacle, but solitary astronomers seldom have an audience to share their excitement. Seventeen hours later in the Americas a second wave of auroras turned night to day as far south as Panama. People could read the newspaper by their crimson and green light. Gold miners in the Rocky Mountains woke up and ate breakfast at 1 A.M., thinking the sun had risen on a cloudy day. Telegraph systems became unusable across Europe and North America.

The news media of the day looked for researchers able to explain the phenomena, but at the time scientists scarcely understood auroral displays at all. Were they meteoritic matter from space, reflected light from polar icebergs or a high-altitude version of lightning? It was the Great Aurora of 1859 itself that ushered in a new paradigm. The October 15 issue of *Scientific American* noted that "a connection between the northern lights and forces of electricity and magnetism is now fully established." Work since then has established that auroral displays ultimately originate in violent events on the sun, which fire off huge clouds of plasma and mo-

PAT RAWLINGS SA/C



mentarily disrupt our planet's magnetic field.

The impact of the 1859 storm was muted only by the infancy of our technological civilization at that time. Were it to happen today, it could severely damage satellites, disable radio communications and cause continent-wide electrical blackouts that would require weeks or longer to recover from. Although a storm of that magnitude is a comfortably rare once-in-500-years event, those with half its intensity hit every 50 years or so. The last one, which occurred on November 13, 1960, led to worldwide geomagnetic disturbances and radio outages. If we make no preparations, by some calculations the direct and indirect costs of another superstorm could equal that of a major hurricane or earthquake.

The Big One

The number of sunspots, along with other signs of solar magnetic activity, waxes and wanes on an 11-year cycle. The current cycle began this past January; over the coming half a decade, solar activity will ramp up from its current lull. During the previous 11 years, 21,000 flares and 13,000 clouds of ionized gas, or plasma, exploded from the sun's surface. These phenomena, collectively termed solar storms, arise from the relentless churning of solar gases. In some ways, they are scaled-up versions of terrestrial storms, with the important difference that magnetic fields lace the solar gases that sculpt and energize them. Flares are analogous to lightning storms; they are bursts of energetic particles and intense x-rays resulting from changes in the magnetic field on a relatively small scale by the sun's standards, spanning thousands of kilometers. So-called coronal mass ejections (CMEs) are analogous to hurricanes; they are giant magnetic bubbles, millions of kilometers across, that hurl billion-ton plasma clouds into space at several million kilometers per hour.

Most of these storms result in nothing more than auroras dancing in the polar skies—the equivalent of a minor afternoon rainstorm on Earth. Occasionally, however, the sun lets loose a gale. No one living today has ever experienced a full-blown superstorm, but telltale signs of them have turned up in some surprising places.

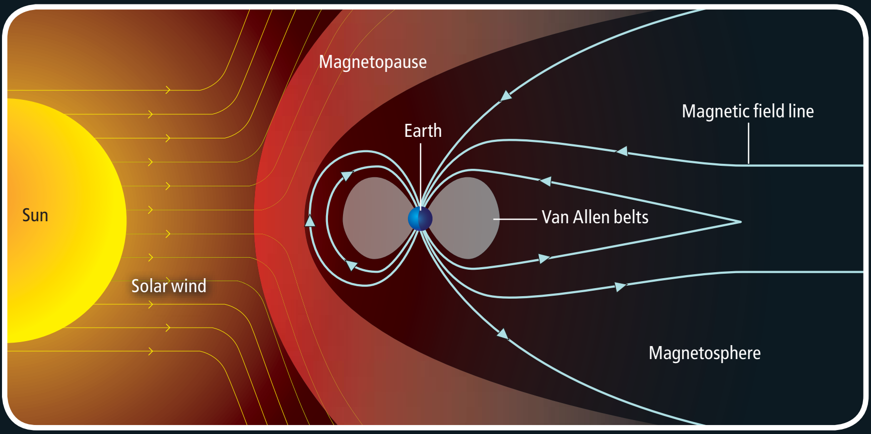
KEY CONCEPTS

- The solar superstorm of 1859 was the fiercest ever recorded. Auroras filled the sky as far south as the Caribbean, magnetic compasses went haywire and telegraph systems failed.
- Ice cores suggest that such a blast of solar particles happens only once every 500 years, but even the storms every 50 years could fry satellites, jam radios and cause coast-to-coast blackouts.
- The cost of such an event justifies more systematic solar monitoring and beefier protection for satellites and the power grid.

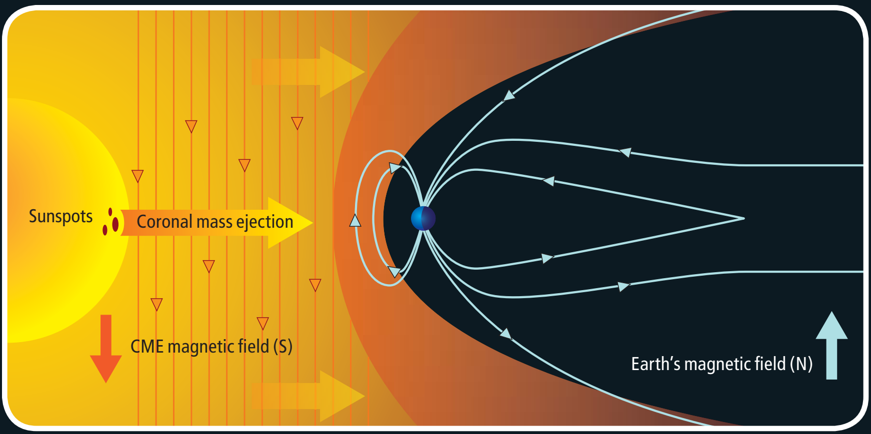
—The Editors

Impact of a Coronal Mass Ejection

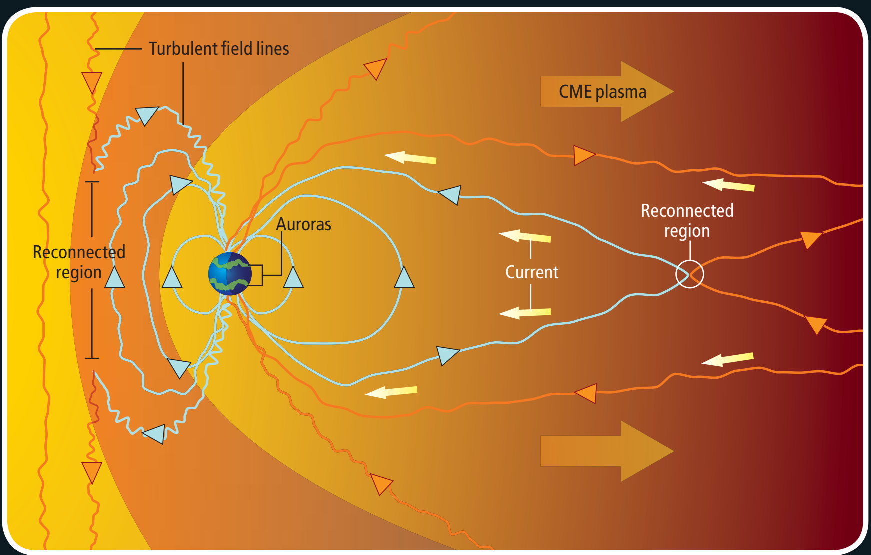
NORMAL CONDITIONS: Earth's magnetic field typically deflects the charged particles streaming out from the sun, carving out a teardrop-shaped volume known as the magnetosphere. On the sun-facing side, the boundary, or magnetopause, is about 60,000 kilometers from our planet. The field also traps particles in a doughnut-shaped region known as the Van Allen belts.



FIRST STAGES OF IMPACT: When the sun fires off a coronal mass ejection (CME), this bubble of ionized gas greatly compresses the magnetosphere. In extreme cases such as superstorms, it can push the magnetopause into the Van Allen belts and wipe them out.



MAGNETIC RECONNECTION: The solar gas has its own magnetic field, and as it streams past our planet, it stirs up turbulence in Earth's magnetic field. If this field points in the opposite direction as Earth's, the two can link up, or reconnect—releasing magnetic energy that accelerates particles and thereby creates bright auroras and powerful electric currents.



The 1859 Superstorm

The authors have reconstructed what happened in 1859, based in part on similar (though less intense) events seen by modern satellites. UTC is Coordinated Universal Time—basically, Greenwich Mean Time.

August 26
Large sunspot group appears near longitude 55 degrees west on the sun; first CME possibly launched.

SUNSPOTS

August 28
CME arrives at Earth with a glancing blow because of the solar longitude of its source; its magnetic orientation is northward.

August 28 07:30 UTC
Greenwich Magnetic Observatory detects a disturbance, signaling compression of the magnetosphere.

CORONAL MASS EJECTION

August 28 22:55 UTC
Main storm phase begins, with large magnetic disturbances, telegraphic disruptions and auroral sightings as far south as magnetic latitude 25 degrees north.

AURORA SIGHTINGS

August 30
Geomagnetic disturbances from first CME end.

September 1 11:15 UTC
Astronomer Richard C. Carrington, among others, sights a white-light flare on the sun; the large sunspot group has rotated to longitude 12 degrees west.

X-RAY FLARE

September 2 05:00 UTC
Greenwich and Kew magnetic observatories detect disturbances followed immediately by geomagnetic chaos; second CME arrives at Earth within 17.5 hours, traveling at 2,380 kilometers per second with southward magnetic orientation; auroras appear down to magnetic latitude 18 degrees north.

AURORA SIGHTINGS

September 3–4
Main phase of geomagnetic disturbances from second CME ends; scattered auroral sightings continue, but with diminishing intensity.

In ice-core data from Greenland and Antarctica, Kenneth G. McCracken of the University of Maryland has discovered sudden jumps in the concentration of trapped nitrate gases, which in recent decades appear to correlate with known blasts of solar particles. A nitrate anomaly found for 1859 stands out as the biggest of the past 500 years, with the severity roughly equivalent to the sum of all the major events of the past 40 years.

As violent as it was, the 1859 superstorm does not appear to have been qualitatively different from lesser events. The two of us, along with many other researchers, have reconstructed what happened back then from contemporary historical accounts as well as scaled-up measurements of milder storms in recent decades, which have been studied by modern satellites:

1. The gathering storm. On the sun, the preconditions for the 1859 superstorm involved the appearance of a large, near-equatorial sunspot group around the peak of the sunspot cycle. The sunspots were so large that astronomers such as Carrington could see them with the naked (but suitably protected) eye. At the time of the initial CME released by the storm, this sunspot group was opposite Earth, putting our planet squarely in the bull's-eye. The sun's aim need not be so exact, however. By the time a CME reaches Earth's orbit, it typically has fanned out to a width of some 50 million kilometers, thousands of times wider than our planet.

2. First blast. The superstorm released not one but two CMEs. The first may have taken the customary 40 to 60 hours to arrive. The magnetometer data from 1859 suggest that the magnetic field in the ejected plasma probably had a helical shape. When it first hit Earth, the field was pointing north. In this orientation, the field reinforced Earth's own magnetic field, which minimized its effects. The CME did compress Earth's magnetosphere—the region of near-Earth space where our planet's magnetic field dominates the sun's—and registered at magnetometer stations on the ground as what solar scientists call a sudden storm commencement. Otherwise it went unnoticed. As plasma continued to stream past Earth, however, its field slowly spun around. After 15 hours, it opposed rather than reinforced Earth's field, bringing our planet's north-pointing and the plasma cloud's south-pointing field lines into contact. The field lines then reconnected into a simpler shape, releasing huge amounts of stored energy. That is when the telegraph disruptions and auroral displays commenced. Within a day or two the plasma passed by Earth, and our planet's geomagnetic field returned to normal.

3. X-ray flare. The largest CMEs typically coincide with one or more intense flares, and the 1859 superstorm was no exception. The visible flare observed by Carrington and others on September 1 implied temperatures of nearly 50 million kelvins. Accordingly, it probably emitted not only visible light but also x-rays and gamma rays. It was the most brilliant solar flare ever recorded, bespeaking enormous energies released into the solar atmosphere. The radiation hit Earth after the light travel time of eight and a half minutes, long before the second CME. Had shortwave radios existed, they would have been rendered useless by energy deposition in the ionosphere, the high-altitude layer of ionized gas that reflects radio waves. The x-ray energy also heated the upper atmosphere and caused it to bloat out by tens or hundreds of kilometers.

4. Second blast. Before the ambient solar-wind plasma had time to fill in the cavity formed by the passage of the first CME, the sun fired off

IT'S RAINING PROTONS

Like terrestrial hurricanes and thunderstorms, solar storms can wreak havoc in multiple ways.

- Solar flares are relatively small-scale explosions that emit bursts of radiation. They cause enhanced radio absorption in the so-called D layer of Earth's ionosphere, interfering with Global Positioning System signals and shortwave reception. Flares also heat the upper atmosphere, puffing it up and increasing drag on satellites.

- Coronal mass ejections (CMEs) are giant bubbles of ionized gas. If Earth is caught in their crosshairs, they can induce electric currents that surge into pipelines, cables and electrical transformers.

- Solar proton events are floods of high-energy protons that occasionally accompany flares and CMEs. They can zap data in electronic circuits and give astronauts and airline passengers an extra dose of radiation.

AURORA BOREALIS, shown here in Njardvík, Iceland, is the most photogenic result of solar activity. These dramatic light shows occur when charged particles, mostly from the solar wind, collide with gases in Earth's upper atmosphere. The colors represent emissions from different chemical elements. Auroras are typically confined to polar regions but can dance across tropical skies during a major solar storm.

OPPOSITE PAGE: ILLUSTRATIONS BY MELISSA THOMAS; CARNEGIE INSTITUTION OF WASHINGTON (*sunspots*); SOHO/NASA (*coronal mass ejection* and *solar flare*); THIS PAGE: ARCTIC-IMAGES/CORBIS (*aurora*) a second CME. With little material to impede it, the CME reached Earth within 17 hours. This time the CME field pointed south as it hit, and the geomagnetic mayhem was immediate. Such was its violence that it compressed Earth's magnetosphere (which usually extends about 60,000 kilometers) to 7,000 kilometers or perhaps even into the upper stratosphere itself. The Van Allen radiation belts that encircle our planet were temporarily eliminated, and huge numbers of protons and electrons were dumped into the upper atmosphere. These particles may have accounted for the intense red auroras seen in much of the world.

5. Energetic protons. The solar flare and the intense CMEs also accelerated protons to energies of 30 million electron volts or higher. Across the Arctic, where Earth's magnetic field affords the least protection, these particles penetrated to an altitude of 50 kilometers and deposited additional energy in the ionosphere. According to Brian C. Thomas of Washburn University, the proton shower from the 1859 superstorm reduced stratospheric ozone by 5 percent. The layer took four years to recover. The most powerful protons, with energies above one billion electron volts, reacted with the nuclei of nitrogen and oxygen atoms in the air, spawning neutrons and creating the nitrate abundance anomalies. A rain of neutrons reached the ground in what is now called a ground level event, but no human technology was available to detect this onslaught. Fortunately, it was not hazardous to health.

6. Massive electric currents. As the auroras spread from the usual high latitudes to low latitudes, the accompanying ionospheric and auroral electric currents induced intense, continent-spanning currents in the ground. These currents found their way into telegraph circuitry. The multiampere, high-voltage discharges caused near electrocutions and were reported to have burned down several telegraph stations.

Toasted Satellites

When a large geomagnetic storm happens again, the most obvious victims will be satellites. Even under ordinary conditions, cosmic-ray particles erode solar panels and reduce power generation by about 2 percent annually. Incoming particles also interfere with satellite electronics. Many communications satellites, such as Anik E1 and E2 in 1994 and Telstar 401 in 1997, have been compromised or lost in this way. A large solar storm can cause one to three years' worth of satellite lifetime loss in a matter of hours and produce hundreds of glitches, ranging from errant but harmless commands to destructive electrostatic discharges.

To see how communications satellites might fare, we simulated 1,000 ways a superstorm might unfold, with intensities that varied from the worst storm of the Space Age (which occurred on October 20, 1989) to that of the 1859 superstorm. We found that the storms would not only degrade solar panels as expected but also lead to the significant loss of transponder revenue. The total cost would often exceed $20 billion. We assumed that satellite owners and designers would have mitigated the effects by maintaining plenty of spare transponder capacity and a 10 percent power margin at the time of their satellite's launch. Under less optimistic assumptions, the losses would approach $70 billion, which is comparable to a year's worth of revenue for all communications satellites. Even this figure does not include the collateral economic losses to the customers of the satellites.

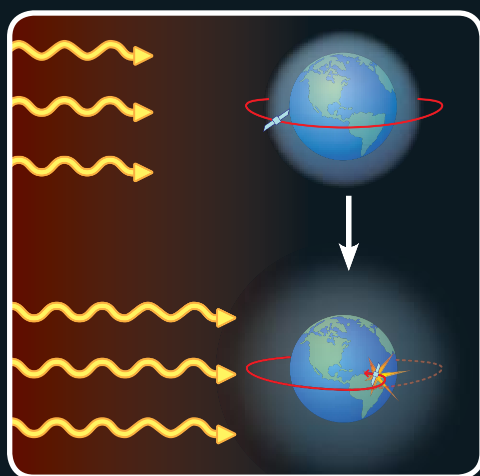
Fortunately, geosynchronous communications satellites are remarkably robust against once-a-decade events, and their life spans have

ILLUSTRATIONS BY MELISSA THOMAS

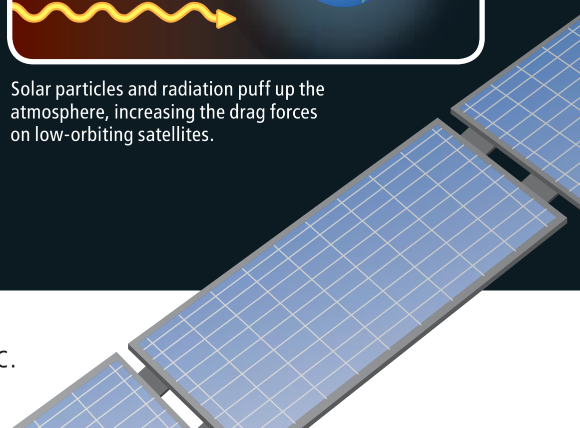
[EFFECTS ON SATELLITES]

Feeling the Full Brunt

The harshness of space takes a toll on satellites even at the best of times. A superstorm would cause years' worth of damage within a few hours.



Solar particles and radiation puff up the atmosphere, increasing the drag forces on low-orbiting satellites.



ZAPPING YOUR COMPUTER

A superstorm might well have strange effects on electronics. The high-energy protons that reach the ground produce neutrons that pass right through the shielding around satellite and avionics systems. (Most computer systems lack even this shielding.)

Extensive background radiation studies by IBM in the 1990s suggest that computers typically experience about one cosmic-ray-induced error per 256 megabytes of RAM per month. If so, a superstorm, with its unprecedented radiation fluxes, could cause widespread computer failures. Fortunately, in such instances most users could simply reboot.

grown from barely five years in 1980 to nearly 17 years today. For solar panels, engineers have switched from silicon to gallium arsenide to increase power production and reduce mass. This move has also provided increased resistance to cosmic-ray damage. Moreover, satellite operators receive advanced storm warnings from the National Oceanic and Atmospheric Administration's Space Weather Prediction Center, which allows them to avoid complex satellite maneuvers or other changes during the time when a storm may arrive. These strategies would doubtless soften the blow of a major storm. To further harden satellites, engineers could thicken the shielding, lower the solar panel voltages to lessen the risk of runaway electrostatic discharges, add extra backup systems and make the software more robust to data corruption.

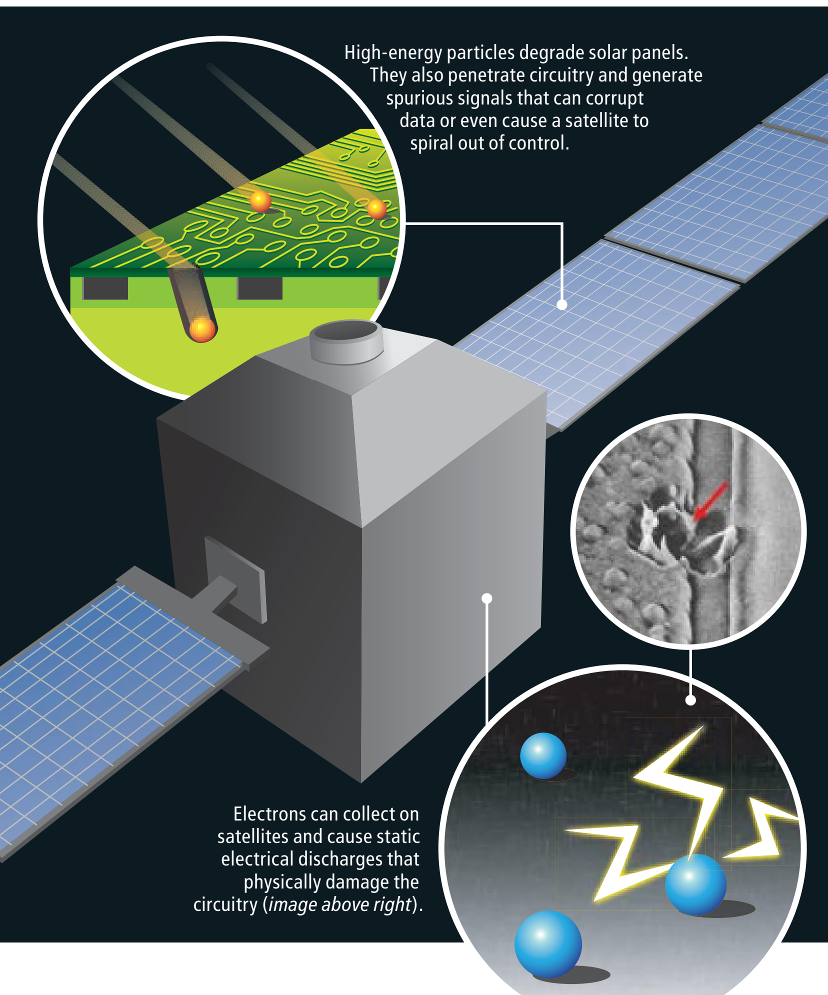
It is harder to guard against other superstorm effects. X-ray energy deposition would cause the atmosphere to expand, enhancing the drag forces on military and commercial imaging and communications satellites that orbit below 600 kilometers in altitude. Japan's Advanced Satellite for Cosmology and Astrophysics experienced just such conditions during the infamous Bastille Day storm on July 14, 2000, which set in motion a sequence of attitude and power losses that ultimately led to its premature reentry a few months later. During a superstorm, low-orbiting satellites would be at considerable risk of burning up in the atmosphere within weeks or months of the event.

Lights Out

At least our satellites have been specifically designed to function under the vagaries of space weather. Power grids, in contrast, are fragile at the best of times. Every year, according to estimates by Kristina Hamachi-LaCommare and Joseph H. Eto, both at Lawrence Berkeley National Laboratory, the U.S. economy takes an $80-billion hit from localized blackouts and brownouts. Declining power margins over the past decade have also left less excess capacity to keep up with soaring demands.

During solar storms, entirely new problems arise. Large transformers are electrically grounded to Earth and thus susceptible to damage caused by geomagnetically induced direct cur-

SUSAN CLERMONT (*Odenwald*); COURTESY OF JAMES L. GREEN (*Green*); JPL (*satellite damage*)

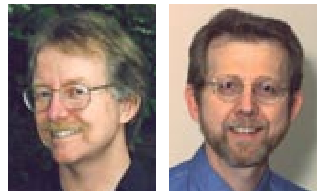


How to Prepare

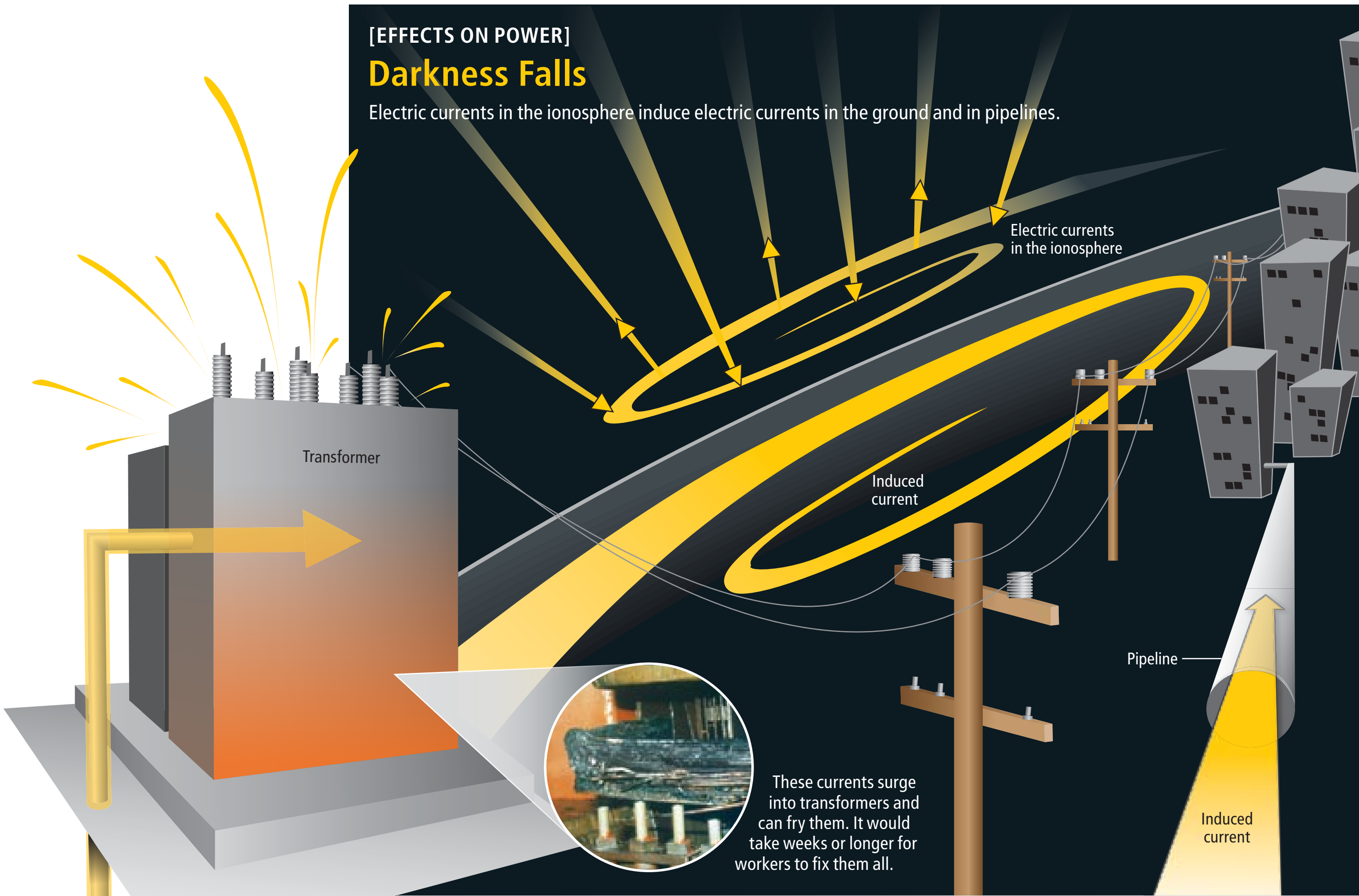
If a storm were on its way, we could do the following:

- Satellite operators put off critical command sequences. During the storm itself, they monitor their birds and override any spurious commands.
- GPS users switch to backup navigation systems.
- Astronauts avoid space walks.

[THE AUTHORS]



Sten F. Odenwald (*left*) is an astronomy professor at the Catholic University of America and a senior scientist at SP Systems in Greenbelt, Md. He is an award-winning science popularizer and author who works under contract at the NASA Goddard Space Flight Center. Odenwald's main areas of research are the cosmic infrared background and space weather phenomenology. His passion for astronomy was kindled at age 11 by *The Outer Limits* TV show. **James L. Green** (*right*) is director of NASA's Planetary Science Division. He has studied planetary magnetospheres and is a co-investigator on the IMAGE magnetospheric mission. He enjoys history and is working on a publication about balloons in the American Civil War. It was his interest in this time period that led him to run across more than 200 newspaper articles about the 1859 storm.



rent (DC). The DC flows up the transformer ground wires and can lead to temperature spikes of 200 degrees Celsius or higher in the transformer windings, causing coolant to vaporize and literally frying the transformer. Even if transformers avoid this fate, the induced current can cause their magnetic cores to saturate during one half of the alternating-current power cycle, distorting the 50- or 60-hertz waveforms. Some of the power is diverted to frequencies that electrical equipment cannot filter out. Instead of humming at a pure pitch, transformers would begin to chatter and screech. Because a magnetic storm affects transformers all over the country, the condition can rapidly escalate to a network-wide collapse of voltage regulation. Grids operate so close to the margin of failure that it would not take much to push them over.

According to studies by John G. Kappenman of Metatech Corporation, the magnetic storm of May 15, 1921, would have caused a blackout affecting half of North America had it happened today. A much larger storm, like that of 1859, could bring down the entire grid. Other industrial countries are also vulnerable, but North America faces greater danger because of its proximity to the north magnetic pole. Because of the physical damage to transformers, full recovery and replacement of damaged components might take weeks or even months. Kappenman testified to Congress in 2003 that "the ability to provide meaningful emergency aid and response to an impacted population that may be in excess of 100 million people will be a difficult challenge."

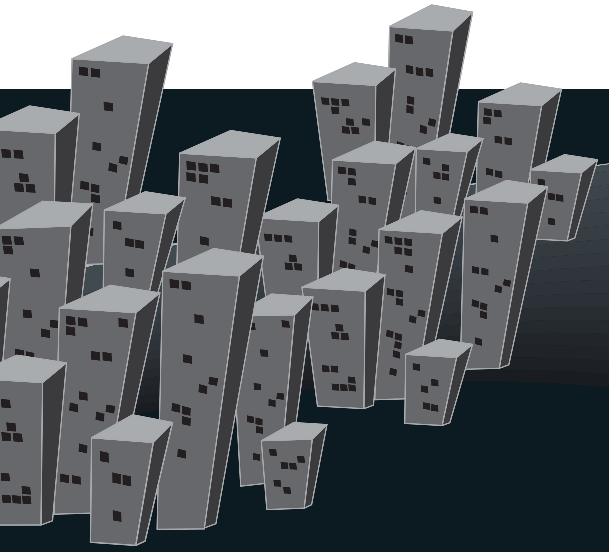
A superstorm will also interfere with radio signals, including those of the Global Positioning System (GPS) and related systems. Intense solar flares not only disturb the ionosphere, through which timing signals propagate, but also produce increased radio noise at GPS frequencies. The result would be position errors of 50 meters or more, rendering GPS useless for many military and civilian applications. A similar loss of precision occurred during the October 29, 2003, storm, which shut down the Wide Area Augmentation System, a radio network

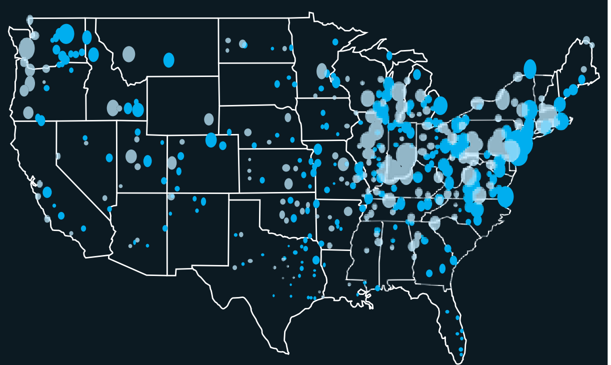
WOULD ASTRONAUTS GET FRIED?

One piece of good news about superstorms is that the radiation dosage to astronauts in low-Earth orbit would probably not be life-threatening. Lawrence W. Townsend of the University of Tennessee calculated a superstorm dose of about 20 rads (0.2 gray), which is comparable to the 30-day cumulative exposure limits set by NASA.

On the other hand, this one-time event would still be more radiation than someone living on the ground would receive from natural environmental sources over the course of 70 years. Airline passengers might receive a dose equal to a CT scan.

ILLUSTRATIONS BY MELISSA THOMAS; COURTESY OF JOHN KAPPENMAN (*transformer melting* and *U.S. map*)





The entire East Coast and much of the rest of the country would lose power. This map shows the blacked-out regions expected from a severe storm like that of 1921, which would induce ground fields of about 20 volts per kilometer. Scientists have yet to model the effects of a full-blown 1859-like storm on the power grid.

that improves the accuracy of GPS position estimates. Commercial aircraft had to resort to in-flight backup systems.

High-energy particles will interfere with aircraft radio communications, especially at high latitudes. United Airlines routinely monitors space weather conditions and has on several occasions diverted polar flights to lower altitudes and latitudes to escape radio interference. A superstorm might force the rerouting of hundreds of flights not just over the pole but also across Canada and the northern U.S. These adverse conditions might last a week.

Getting Ready

Ironically, society's increasing vulnerability to solar storms has coincided with decreasing public awareness. We recently surveyed newspaper coverage of space weather events since the 1840s and discovered that a significant change occurred around 1950. Before this time, magnetic storms, solar flares and their effects often received lavish, front-page stories in newspapers. The *Boston Globe* carried a two-inch headline "U.S. Hit by Magnetic Storm" on March 24, 1940. Since 1950, though, such stories have been buried on inside pages.

Even fairly minor storms are costly. In 2004 Kevin Forbes of the Catholic University of America and Orville Chris St. Cyr of the NASA Goddard Space Flight Center examined the electrical power market from June 1, 2000, to December 31, 2001, and concluded that solar storms increased the wholesale price of electricity during this period by approximately $500 million. Meanwhile the U.S. Department of Defense has estimated that solar disruptions to government satellites cost about $100 million a year. Furthermore, satellite insurers paid out nearly $2 billion between 1996 and 2005 to cover commercial satellite damages and losses, some of which were precipitated by adverse space weather.

We would be well served by more reliable warnings of solar and geomagnetic storms. With adequate warning, satellite operators can defer critical maneuvering and watch for anomalies that, without quick action, could escalate into critical emergencies. Airline pilots could prepare for an orderly schedule of flight diversions. Power grid operators could watch susceptible network components and make plans to minimize the time the grid might be out of commission.

Agencies such as NASA and the National Science Foundation have worked over the past 20 years to develop space-weather forecasting capabilities. Currently NOAA's Space Weather Prediction Center provides daily space weather reports to more than 1,000 businesses and government agencies. Its annual budget of $6 million is far less than the nearly $500 billion in revenues generated by the industries supported by these forecasts. But this capability relies on a hodgepodge of satellites designed more for research purposes than for efficient, long-term space weather monitoring.

Some researchers feel our ability to predict space weather is about where NOAA was in predicting atmospheric weather in the early 1950s. From a monitoring perspective, what are needed are inexpensive, long-term space buoys to monitor weather conditions using simple, off-the-shelf instruments. In the meantime, scientists have a long way to go to understand the physics of solar storms and to forecast their effects. If we really want to safeguard our technological infrastructure, we will have to redouble our investment in forecasting, modeling and basic research to batten down for the next solar tempest. ■

MORE TO EXPLORE

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General information about the impacts of solar storms can also be found at **www.solarstorms.org**

Sten F. Odenwald's popular Web site Astronomy Cafe is available at **www.astronomycafe.net**