

THE COMING

In 1859, the Sun unleashed its biggest storm in 450 years. We're more

SOLAR SUP

Hot plasma arcs above a sunspot over the Sun's limb. The ultraviolet scene, captured in late 2006, reveals fine-scale structure extending from the mottling, or granulation, on the Sun's surface and into its lower atmosphere. Hinode, the most advanced solar telescope ever flown in space, launched September 22, 2006, and returned this view.

JAXA/NASA/Hinode

Any disaster capable of causing large-scale blackouts, disrupting communications networks, and damaging satellites is something to prepare for. These are just a few of the effects that follow powerful eruptions from the Sun.

Scientists now recognize that we haven't seen the worst the Sun can throw at us. Solar flares in 1859 kicked off a storm so massive that, if it happened today, could cripple much of the technology we've come to rely on.

vulnerable than ever to its next blast. **by Sten Odenwald**

PERSTORM

Solar cycles

The Sun's storminess rises and falls every 11 years, on average. Cycle 23 is now drawing to a close. Since 1996, this cycle has produced more than 21,000 flares — giant magnetic explosions on the Sun's surface. It has launched 13,000 coronal mass ejections (CMEs) — billion-ton clouds of ionized gas (plasma) that race through interplanetary space.

Both events can trigger spectacular auroral displays (the so-called northern and southern lights). But the same radiation that produces these beautiful glows can damage satellite electronics. Radiation from solar flares also can ionize the atmosphere so strongly that radio communication at some frequencies is impossible for hours. Electrical currents flowing at the top of the atmosphere can induce currents on the ground in long conductors, like the national power grid, and damage and destroy transformers and other equipment.

As solar cycles go, Cycle 23 was well behaved. Its worst blasts, which included a record-breaking flare November 4, 2003, spawned intense activity now known in space-weather circles as the Halloween Storms. They crippled instruments on some spacecraft, including NASA's Mars Odyssey, and triggered a blackout in Sweden.

But that, researchers say, was nothing. Once every few centuries, the Sun erupts with an event unlike anything modern scientists have ever experienced.

The 1859 superstorm

Between August 28 and September 6, 1859, the Sun produced one of its most spectacular solar storms in the last 450 years. Scientists who reconstructed this event from historical data put it in a class by itself. They call it a superstorm. Here's what it was like.

The first CME arrived at 7h30m Universal Time (UT) August 28, 1859. Doz-

ens of instruments around the world recorded its passage as a minor magnetic glitch. Yet, even by modern standards, this was a major storm.

Normally, a storm's north-directed magnetic field squelches any auroral displays. But despite its incorrect magnetic orientation, the 1859 storm was so intense it spawned aurorae seen as far south as Athens, Greece. Why? Some hours before the bubble of hot gas reached Earth, it emitted a gale of fast-moving protons. These particles raced ahead of the cloud and were absorbed by Earth's atmosphere. These particles, not the CME itself, produced the light show.

A few days later, a second CME raced past our planet. British astronomers Richard Carrington and Richard Hodgson, who happened to be observing the Sun, witnessed the launch of this massive cloud by a rare and powerful solar flare (see "Stars on the Sun," p. 36).

On September 1, 1859, two British astronomers independently observed a rare and powerful flare on the Sun's disk. It was this eruption that launched round two of the solar superstorm.

Richard Carrington and Richard Hodgson were observing sunspots by projecting the Sun's image onto a screen. Carrington had completed drawing sunspot groups when, at 11:18 A.M. Greenwich Mean Time, he

noticed "two patches of intensely bright and white light" near the largest group.

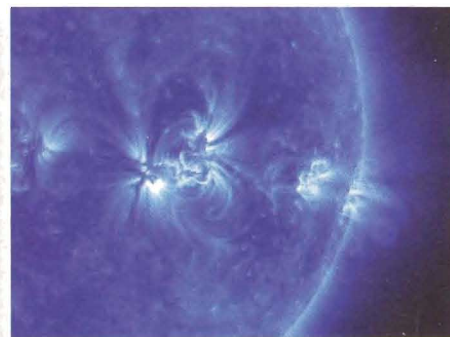
Hodgson described the flare as a "brilliant star of light, much brighter than the Sun's surface, and most dazzling to the protected eye." The show ended 5 minutes later.

In that time, Carrington noted, the patches of light moved some 35,000 miles (56,000 km) across the Sun's disk. He saw no changes to

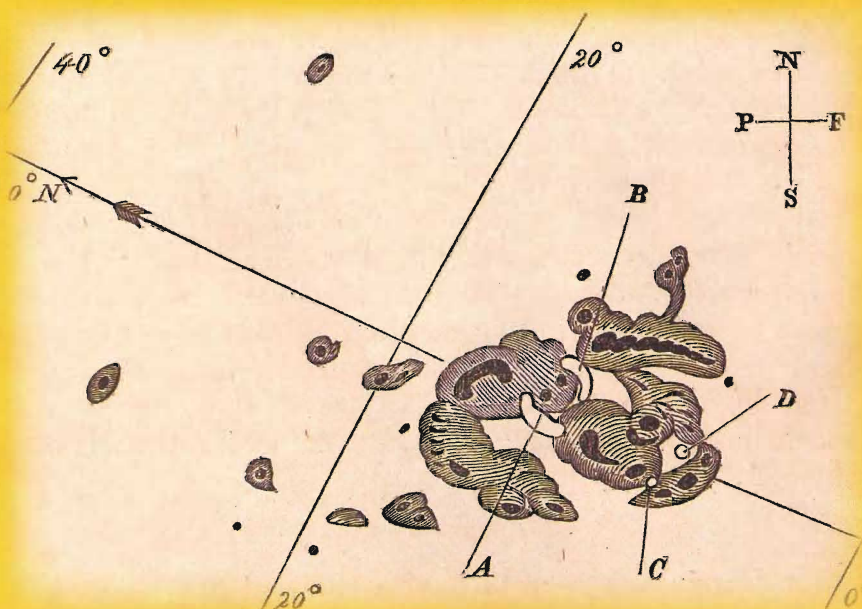
the spots themselves, and concluded that "the phenomenon took place at an elevation considerably above the general surface of the Sun."

What these observers couldn't see, of course, was the massive CME this flare launched toward Earth. But Carrington suggested the flare might be related to the exceptional magnetic storm that followed 17 hours later.

— Francis Reddy



Magnetic loops arch above solar active regions June 9, 2007. These areas of intense magnetism often are sources of solar storms. NASA/STEREO



Richard Carrington sketched the massive white-light flare he witnessed September 1, 1859. The eruption began at the locations marked A and B. The eruption subsided 5 minutes later at points C and D. Linda Hall Library

over some celestial battle. They stood and gawked by the millions and wrote detailed eyewitness accounts to newspapers. Miners awoke after midnight and broke camp, thinking dawn had arrived. Thousands of people comfortably read newspapers under the night sky's wavering crimson glow.

In this pre-Civil War era, telegraph outages and instrument fires proved to be the only technological impact. The currents generated underground by the storm's shifting magnetic and electric fields were so powerful they set fires in telegraph offices on both sides of the Atlantic. In Washington, D.C., they nearly electrocuted telegraph operator Frederick Royce.

Today, the calamity such a storm would cause would have no historical precedent. At no other time has the web of technology so completely engulfed our day-to-day lives. Billions of people are in close personal contact with the technologies most prone to space weather's effects. Luckily, superstorms seem to be rare events for a star like our Sun.

Deep freeze

Deep within ice crystals in Greenland and Antarctica, nitrate molecules have collected in trapped gases since 1561. Scientists Michael Smart, Donald Shea, and Kenneth McCracken at the U.S. Air Force Research Lab at Wright-Patterson Air Force Base, Ohio, and the University of Maryland discovered that nitrate concentrations rise and fall with solar activ-

Sten Odenwald is a professor of astronomy at Catholic University in Washington. He is an avid science popularizer and author.

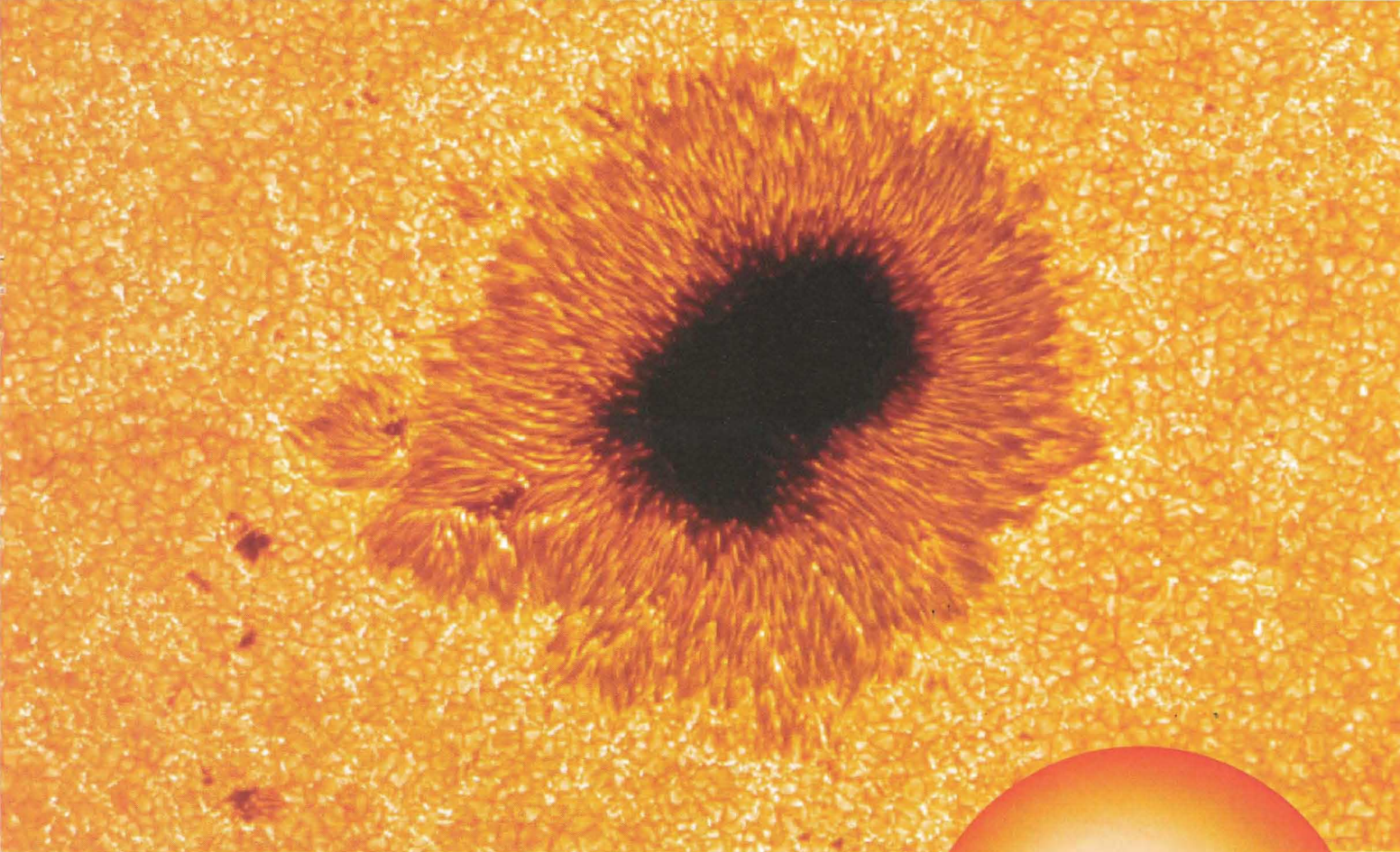
This CME had everything going for it. It was fast: In just 17 hours, the cloud swept across the entire inner solar system at a speed of 5 million mph (8 million km/h). The dense wall of plasma also possessed a southward-pointing magnetic field, which enhanced its potential impact. At 4h40m UT September 2, part of this monster plasma cloud brushed past Earth.

Our planet resides in a protective bubble created by its magnetic field and ions trapped inside it. Within minutes of the cloud's impact, the entire Sun-facing hemisphere of Earth's magnetic bubble was compressed until it reached the outer atmosphere's fringes. The blow instantly

affected the ozone layer, reducing this ultraviolet-absorbing gas so much — by about 5 percent — that it took years to recover to pre-storm levels.

The night-side portion of Earth's magnetic field became a complex, tangled web of field lines trying to sort themselves out within an enormous volume of space. This magnetic upheaval, invisible to the human eye, may have continued for more than a day.

From the ground, spectacular crimson aurorae could be seen as far south as equatorial Central America and Bombay, India. Predictably, people mistook the lights for distant cities on fire, or imagined them as specters dancing in glee



This Hinode image provides the sharpest-ever look into a modest sunspot about 4 times Earth's size. Rising and falling cells of hot gas create the mottled appearance, called granulation, of the Sun's normal surface. Sunspots appear dark because their strong magnetic fields suppress rising columns of hot gas and allow the spots to cool. JAXA/NASA/Hinode

ity. Nitrates are a particularly good barometer of powerful radiation storms called solar proton events (SPEs). In the 450 years covered by the frozen record, the biggest SPE was the 1859 superstorm.

The satellite industry uses the storm event that occurred August 4, 1972, as its worst case. According to the nitrate record, 19 events more intense than this storm have occurred since 1561. In addition, they occurred, on average, in 23-year intervals.

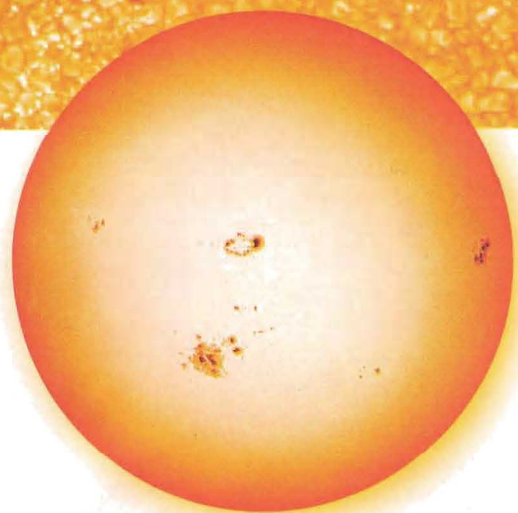
The August 1972 event, which was one-fourth as strong as the superstorm, is the only one that even comes close to its power since 1965. In fact, during the last 4 decades, the Sun has produced the fewest large SPEs of any 40-year span back to 1670.

So, if you wanted to build satellites to endure the rigors of the space environment, the solar storms of the past 40 years' are the wrong examples to use. In truth, things can get much nastier than these storms indicate.

Scientists can't predict when one of these superstorms will occur. Here's what we can expect if Cycle 24 launches one our way.

The next superstorm

The superstorm likely would come sometime between 2010 and 2012, near the peak of the Sun's activity cycle. The most favorable months would be March or September,



Enormous sunspots more than 10 times Earth's diameter peppered the Sun in October 2003. These spots launched the record-breaking Halloween solar storms. NASA/ESA/SOHO

during the equinoxes, when solar storms can more easily impact Earth.

The first warning sign might be the presence of a large, distorted sunspot group. Scientists expect dozens of small X-ray flares (classed as X-1 and up) from such systems. They also can produce a few moderate-intensity (X-10 and up) flares. These occurrences signal highly disturbed magnetic conditions within the spot. Each flare would cause notable short-wave radio blackouts, but only amateur radio operators and some emergency services might take notice.

The August 1972 solar storm serves as the satellite industry's worst case, but the 1859 superstorm packed 4 times its punch.



This composite of Solar and Heliospheric Observatory images shows the Sun's disk in ultraviolet light and the tail end of a coronal mass ejection (CME) blasting into space. These enormous eruptions launch billions of tons of ionized gas across the solar system. Those directed Earth's way can affect satellites, radio communications, and power systems. NASA/ESA/SOHO

Unless the sunspot group launched a white-light flare visible to lucky amateur and professional solar observers, the first to see the eruption would be an armada of aging solar research satellites, such as Hinode, STEREO, and the Solar Dynamics Observatory.

An intense blast of X rays and energetic particles would black out every sensor system in space on Earth's daylight side. The X-ray pulse also would destroy the atmosphere's ionized D-layer. This would instantly black out

short-wave broadcasts across the hemisphere facing the Sun.

The entire Arctic region, perhaps extending to the Great Lakes, would experience a Polar Cap Absorption event, where a flood of solar protons knocks out most radio communications. This would be an instant hazard to air travel and lead to days of delays and costly flight rerouting.

As in 1859, the atmosphere would lose 5 or 10 percent of its ozone layer, which would raise skin cancer rates in

the following years. And the night sky would blaze bright enough to confuse animals — and let humans read beneath eerie auroral glows.

If the superstorm arrived as a so-called double-barreled CME, the first would dazzle Northern Hemisphere skywatchers with spectacular aurorae rivaling those produced by 2003's Halloween Storms. The second punch, launched perhaps a day later, would race through the inner solar system and arrive at Earth within 20 hours.

At impact, all geosynchronous satellites outside Earth's protective magnetic bubble would find themselves immersed in a turbulent magnetic plasma they weren't designed to endure for long. Accelerated by shock waves in the CME, a tremendous pulse of fast-moving protons would race ahead of the cloud and arrive 12 hours earlier. The radiation instantly would invade satellite circuitry. Satellite controllers would record thousands of glitches, some serious enough to end the hardware's operational life.

In a few hours, the effects on satellites alone could result in a loss of \$20 billion in revenue and resources. U.S. Defense Department satellites also would be blinded by varying degrees. The Global Positioning System would report inaccurate positions for a day or more, impacting precision navigation, oil drilling, and some military operations.

As the proton storm's particles enter Earth's

atmosphere, they would initiate nuclear reactions with oxygen and nitrogen atoms. The result would be showers of high-speed neutrons, many of which would reach the ground. Computer systems would crash as so-called "sudden event upsets" violate the integrity of binary information stored in memory.

Lucky break?

Despite this grim scenario, we might actually luck out. Half the time, a CME's magnetic field is oriented north, which minimizes its interaction with Earth's magnetic field. Such a storm would pass by with only moderate impact.

Then again, our luck could go the other way. According to John Kappenman, an electric power engineer at MetaTech Corporation in Goleta, California, a solar storm as severe as one that occurred in 1921 would affect all of North America in an unprecedented blackout. More than 150 million would lose elec-

tricity for days or even weeks. Insidious magnetic storm currents would damage transformers. Replacements would be hard to come by because no domestic suppliers exist.

A 2003 blackout in the northeastern United States involved 50 million people and 12 states and Canadian provinces, and cost \$6 billion over a 24-hour period. During a superstorm event, such effects might linger for a week or more. The cost could exceed \$20 billion a day in lost salaries, spoiled food, and other collateral effects.

Making headlines

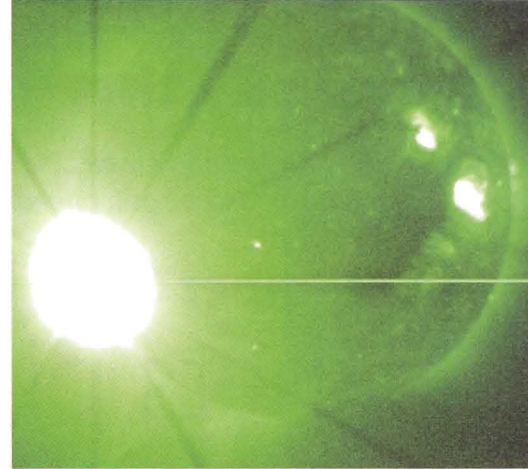
Newspaper accounts often described the last century's solar storms. On March 25, 1940, the *Boston Globe* ran the headline "U.S. Hit by Magnetic Storm" in 2-inch type above the fold.

Editors banked heavily on the average reader knowing what a magnetic storm was. Back then, many people did.

Since the 1950s, solar storms have all but vanished from the front page. Those that make it to print lack details of specific incidents, which mutes their human impact. For instance, the historic March 13, 1989, storm blacked out Quebec for 12 hours and cost several billion dollars. Yet this remarkable cosmic event was never mentioned in major U.S. papers.

It's ironic that we're now far more vulnerable to major solar storms. They now tend to be regarded by the public as entertainment and nighttime spectacle, rather than their historically demonstrated capacity to do serious harm. For instance, the solar storm of September 18, 1946, caused navigation errors that led to a famous plane crash in Gander, Newfoundland, which killed 26 passengers and crew.

The previous sunspot cycle — Cycle 22 — was quite eventful. It led to a costly period



On December 5 and 6, 2006, as solar cycle 23 approached its activity minimum, two powerful X-ray flares exploded on the Sun's limb. The X-ray imager aboard the GOES 13 weather satellite captured this view of the first flare, rated X-9, and experienced slight damage during the event. NGDC/NOAA

of satellite outages and losses totaling, by some estimates, nearly \$3 billion. Satellite industry trade journals spoke about insurance brokers struggling under billion-dollar annual payouts. Collectively, commercial satellites lost about 3 years of their operational lifespan, which translates to tens of billions of dollars in lost profit. There also were several incidents with U.S. electrical power grids, some of which found themselves pushed to near-blackout conditions.

Yet, over the past 5 years, the U.S. Congress has steadily reduced National Oceanic and Atmospheric Administration funding for maintaining and improving our space-weather forecasting ability. The \$6 million annual budget pays for operation of the Space Weather Prediction Center in Boulder, Colorado. Its forecasts, which are used by thousands of companies and government agencies each year, save an estimated \$200 million annually. If this doesn't seem like a bargain, factor in safeguarding the \$500 billion in annual revenues generated by the power industry and satellite commerce.

Our next national blackout could come as a surprise, even though the technology needed to alert us was used during the previous solar cycle. If the cosmic dice fall the wrong way when the Sun's activity peaks again, we may well look back at Cycle 23 as the good old days. ☛



See movies of the Sun from the Hinode solar observatory at www.astronomy.com/toc.

The next superstorm's effects on satellites alone could reach \$20 billion a day in lost revenue and resources.