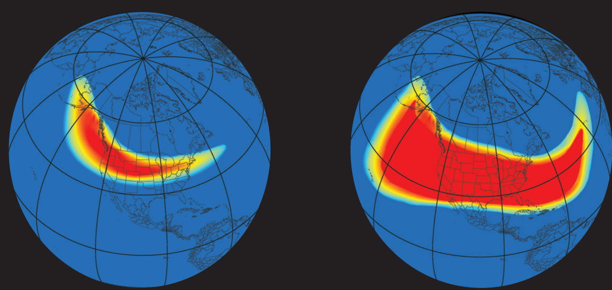
Worse and Worst

By comparing data from the geomagnetic storm in March 1989 [left] with magnetometer readings taken during the May 1921 superstorm, the author has estimated the intensity and geographic reach of the 1921 event [right]. The colored regions show the intense geomagnetic field disturbances caused by the eastward electrojet—a large electric current that builds up in the atmosphere—over North America. Not only was the 1921 storm more intense than the 1989 storm, but it had a much larger geographic footprint. Unfortunately, no data exist to depict the 1921 storm's much larger westward electrojet, but it would have engulfed much of the planet.

SOURCE: ANDREA GRYGO/STORM ANALYSIS CONSULTANTS



ANDREA GRYGO/STORM ANALYSIS CONSULTANTS (2)

The part of the magnetotail that's no longer attached to Earth drifts off into space, while the rest snaps back violently, like a broken rubber band. In the process it forces plasma back into Earth's upper atmosphere, where a large current of more than a million amperes—called an electrojet—builds up at an altitude of about 100 km and produces brilliant auroras. In average-size storms, this electrojet extends only over the globe's higher latitudes, like a halo circling one of the poles. But during very large storms, such as those in 1989 and 1921, it can also reach down to the lower latitudes, where most of the world's population and its infrastructure dwell.

That's not the only means by which the sun can upset Earth's geomagnetic balance. Coronal mass ejections that are big enough can collide directly with Earth's magnetosphere, releasing enough energy to collapse it on the daytime side of the planet from more than 64 000 km to less than 25 000 km in just a minute or two. The solar wind can buffet the magnetosphere, creating giant electromagnetic waves, much as hurricane winds kick up surf on the ocean. At lower latitudes, space weather can set off geomagnetic activity of a lesser intensity but longer duration, which can be as damaging to electric grids near the equator as other types of storms can be at higher latitudes.

But how does all this space weather cause damage down on the ground? It's a multistep process. First, the intense magnetic field variations in the magnetosphere induce electric fields and currents over large areas of Earth's surface. In turn, this geoelectric field creates what are known as geomagnetically induced currents, or GICs, which flow in any available conductor, including high-voltage transmission lines, oil and gas pipelines, railways, and undersea communications cables. These interconnecting networks essentially act as giant antennas that channel the induced currents from the ground. Hit with a 300-ampere GIC, a high-voltage transformer's paper tape insulation will burn, its copper winding will melt, and the transformer will fail, either right then and there or in the future.

High-voltage power grids are designed to withstand the loss of any single important element, such as a substation transformer, and then recover within a half hour or so. For a terrestrial storm like a hurricane or a tornado, this approach works well. But a severe geomagnetic storm covering an entire continent would cause multiple failures all at once. During the first 30 seconds of the 1989 storm, the Quebec grid experienced 15 simultaneous failures—and the unsurprising result was a province-wide blackout. And that storm, remember, was far from the worst Earth has seen.

It took scientists a while to make the connection between something happening on the sun and something happening on Earth. Given the separation between the two events of hours or days and 150 million km, maybe that's not too surprising. The first person to begin connecting the dots was a British amateur astronomer named Richard Carrington, who while doing daily sunspot observations saw a huge "white light" flare on the sun on 1 September 1859. This flare was both preceded and followed by incredible bloodred auroral displays that engulfed the planet from the poles to the tropics.

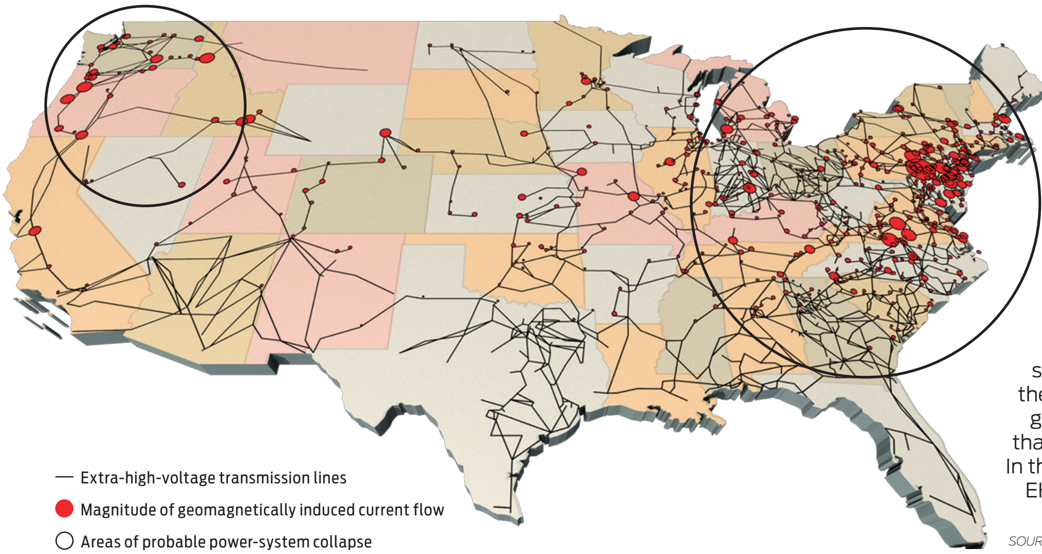
In that era, the only widespread electrotechnology was the telegraph. Electrical current surged through telegraph lines and blew out the batteries that supplied power to them. Telegraph operators were stunned by arcs of electricity leaping from their equipment. Other enterprising operators disconnected the batteries, reconnected the telegraph armature directly to ground, and were able to continue working with just the "celestial" current flowing through their lines.

Over the next few decades, others would expand on the connection between solar activity and geomagnetic storms. But skeptics were also plentiful, including the great physicist Lord Kelvin, who until his death in 1907 remained convinced that Maxwell's equations ruled out any kind of direct influence the sun might have on Earth.

The debate went unresolved until 1959, when the Soviets' Luna 1 satellite finally confirmed the existence of the solar wind. Carrington was long dead by then, of course, but the 1859 storm, one of the most severe in recorded history, is now known as the Carrington event [see "Important Dates in Solar History"].

Could another hemisphere-walloping event occur during the approaching solar max? There's really no telling. The fact is, geomagnetic storms can occur at any point in the solar cycle, and not all solar flares or coronal mass ejections will trigger a storm. Most of them, after all, will be pointed away from Earth. Of the earthbound ones, the damage they do depends on, among other things, the polarity of the magnetic field carried by the solar wind. If the polarity is the same as that of Earth's magnetic field, most of the particles will be deflected harmlessly into space. Eventually, though, we will get a Carrington-class flare that will trigger a superstorm the likes of which we have never seen. For that we are woefully unprepared.

The 1989 geomagnetic storm that blacked out Quebec led to many sobering studies and some potentially promising research, but not much actually changed. No regulations were added to require utility companies to harden their infrastructures, monitor for geomagnetically induced currents, or report transformer failures following geomagnetic storms—and so



Lights Out

A simulation of an extreme geomagnetic storm at 50 degrees geomagnetic latitude shows a widespread collapse of the power grid in the eastern and northwest portions of the United States, which together have a population of more than 130 million people. The black lines indicate extra-high-voltage transmission lines and major substations. The red dots indicate the locations and magnitude of the geomagnetically induced currents that would flow across the network. In this scenario, more than 300 large EHV transformers would either fail or suffer permanent damage.

SOURCE: PETER WARNER/STORM ANALYSIS CONSULTANTS

for the most part, the utilities haven't. There is still no design code for the grid and its components that takes into account threats from space weather.

358 billion kWh
U.S. ANNUAL ELECTRIC ENERGY USAGE IN 1950

3555 billion kWh
U.S. ANNUAL ELECTRIC ENERGY USAGE IN 2000

Meanwhile, the world has become more electrified. In the United States, the extra-high-voltage (EHV) portion of the power grid has grown by a factor of 10 since the late 1950s. China's grid is even more vulnerable, because portions of it now operate at even higher voltages—1000 kilovolts versus a maximum of 765 kV in the United States. Higher voltages can force higher GICs to flow into the grid, because the resistance of high-voltage lines is lower per unit length than it is for lower-voltage lines. But China is just following a worldwide trend: In general, utilities are pushing voltages higher to reduce the amount of energy lost over long distances. But they do so without considering the heightened risk.

Of all the parts of the power grid, high-voltage transformers are among the most likely to fail in a geomagnetic storm and also among the most difficult to replace. If a big storm were to knock out several hundred transformers in one fell swoop, manufacturers wouldn't be able to supply replacements quickly—there is no global stockpile. EHV transformers, which can handle voltages of 345 kV or higher, weigh about 200 tons and cost about $10 million each. Building one requires exquisite, near-artisanal craftsmanship, including meticulously hand winding the paper-tape insulation around the copper winding at the transformer's core. One EHV transformer can take several weeks to assemble and test, and it takes years to train skilled assemblers. Even the largest transformer plants can build only about 30 to 50 per year. With the shortage of skilled labor and specialized materials that would likely accompany a prolonged blackout, simply maintaining that level of output would be a challenge, never mind ramping up new production.

There is a quick and relatively cheap fix to help protect these transformers from geomagnetically induced currents: They can be retrofitted to block the inflow of GICs. But no utilities anywhere routinely protect their multimillion-dollar transformers in this way. Also worrisome is that many transformers in the United States, Western Europe, and Japan are fast approaching the end of their useful lives. The average age of U.S. transformers is about 40 years. Over the decades, each of these devices has likely experienced at least minor overheating and other insults from GICs. An aged transformer that's been exposed to repeated injury is of course far more likely to fail than a brand-new transformer.

Unfortunately for grid operators and others who have to deal with the consequences of geomagnetic disturbances, existing tools for assessing severe space weather fall short. The space-based Solar and Heliospheric Observatory now offers gorgeous images of solar flares as they burst forth from the sun's surface, while the Advanced Composition Explorer satellite makes very precise measurements of the solar wind. As a result, computer models of space weather can now accurately predict when the solar wind will reach Earth. But space weather

Important Dates in Solar History

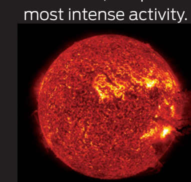
Connecting the dots between solar activity and geomagnetic storms has created a new awareness of extreme events.

SEPTEMBER 1859
Richard Carrington, a British amateur astronomer, observes a "white light" flare on the sun. The accompanying solar superstorm becomes known as the Carrington event.

MAY 1921
Probably the largest solar storm of the 20th century produces auroral observations from the poles to the tropics and damages major portions of the telephone and telegraph systems in the United States and Europe.

MARCH 1989
A large geomagnetic storm knocks out Quebec's power grid, leaving 6 million Canadian customers without electricity for 9 hours and damaging power stations in the northeastern United States.

2012–2013
The sun enters solar maximum, the phase of most intense activity.



MAP: JOHN MACNEILL; PHOTO: NASA SCIENCE VISUALIZATION STUDIO