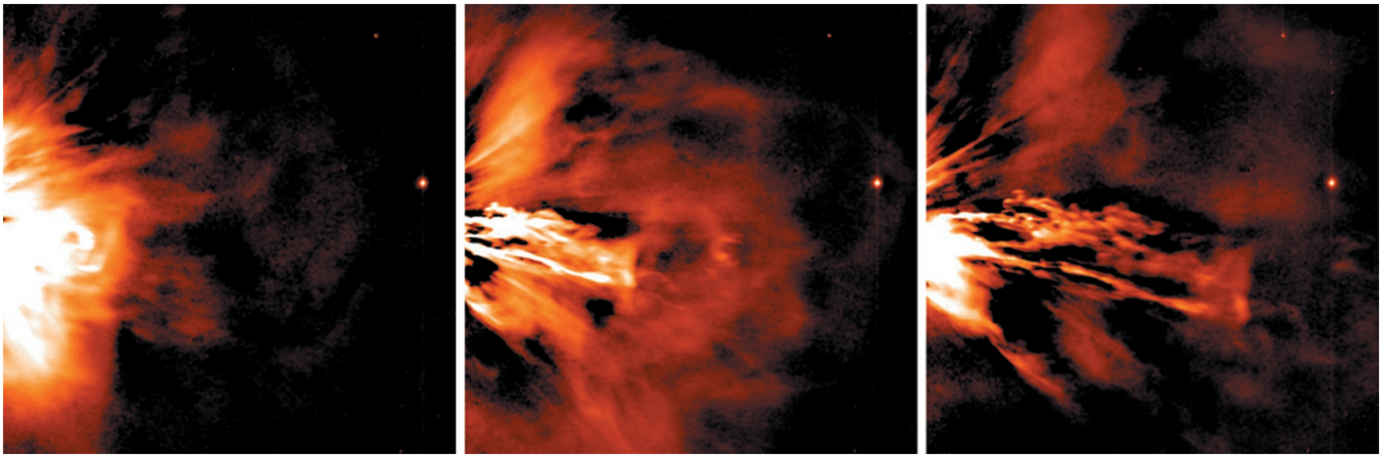
COMMENT

J. DAVIES, STFC/RAL SPACE



This eruption of plasma from the Sun in June 2011, captured by instruments on the STEREO spacecraft, didn't cause a space weather storm on Earth. Others will.

Prepare for the coming space weather storm

We need to improve estimates of geomagnetic storm size, says **Mike Hapgood**, so we can be ready for huge disruptions to electrical systems.

On 13–14 March 1989, Earth experienced its largest geomagnetic storm in decades: a barrage of hot, ionized particles streamed towards the planet, wreaking havoc on its magnetic field and electrical systems. The storm caused a power blackout in Quebec, Canada, leaving 5 million people without electricity for 9 hours in cold weather and causing Can$2 billion (US$2 billion) in damages and losses to business. It also permanently wiped out a US$12-million transformer in the United States, and caused two large UK transformers to be sent back to the factory for repairs. Space agencies temporarily lost track of some 1,600 spacecraft.

We should be prepared for much worse. Even bigger storms have been recorded in the past, although society at the time was less reliant on electrical systems and thus less vulnerable. In September 1859, a huge geomagnetic event disrupted the then-emerging technology of the electric telegraph, shocking operators and sparking fires in telegraph offices. A similar event in May 1921 burnt down a telephone exchange at Karlstad in Sweden. A storm on these scales today would prove disastrous to our highly electronic society. A study by the UK National Grid suggests that a repeat of the 1859 event would leave some regions without power for several months[1]. In the United States, some assessments predict wide-scale disruption with ripple effects lasting for years and an economic impact of several trillion dollars[2].

The source of all this damage is coronal mass ejections (CMEs) — huge eruptions of magnetically charged plasma that occur during magnetic storms in the Sun's atmosphere and that increase the stream of particles in the solar wind by many hundreds of times. When CMEs reach Earth, they can inject large amounts of energy into the planet's magnetic field, causing field variations and driving extra current into electricity grids. The storms can heat and expand the upper atmosphere, nudging the orbits of satellites and space debris, and can charge spacecraft components to dangerous voltages.

There is some capability for forecasting space weather in the short term. The US Space Weather Prediction Center in Boulder, Colorado, can provide warning for strong geomagnetic storms 10–60 minutes in advance with better than 50% reliability, using observations of approaching CMEs by NASA's Advanced Composition Explorer (ACE) spacecraft. That provides a small window in which to apply countermeasures to protect large systems such as the power grid. The newer NASA Solar Terrestrial Relations Observatory (STEREO) has shown that better tracking of CMEs might give reliable warnings 6 hours in advance, with one-hour accuracy. The need to keep improving forecasts was shown in March 2012, when a major CME approaching Earth sparked intense media coverage. Forecasts the day before predicted arrival times that varied ▶

by up to 18 hours. Many were inaccurate, although an experimental forecast from the National Oceanic and Atmospheric Administration (NOAA) in Boulder was close: just one hour early. In the end, that CME produced only a modest space weather event, thanks to the direction of the impacting magnetic fields, which cannot yet be forecast.

In the long term, we still have little sense of what maximum space weather event we should prepare for. Many at-risk electrical systems are designed to withstand events of the type seen in the past 40 years or so of engineering: many power grids, for example, now require that new transformers are able to withstand conditions similar to those experienced in 1989. Last year's earthquake and tsunami in Japan show the dangers of preparing only for an event similar to that seen in recent decades. Instead, we should prepare for a space weather event that might happen only once in 1,000 years.

To do this, scientists need to improve the availability of older space weather data, develop more-sophisticated models to predict future scenarios and ensure that the right systems — from the electric grid to the Global Positioning System (GPS) time-stamps relied on for financial transactions — are prepared properly. That shift is happening, but not quickly enough.

PREPARING FOR THE WORST

The media often airs concerns about solar activity — there have been many stories about the handful of giant solar flares that have occurred since January, for example. But solar flares have a minimal effect on space weather; although they are a good indicator of the amount of energy being released in a solar event, they do not cause CMEs and are not indicators of geomagnetic storms. The media also tends to note that the Sun is heading towards a maximum in its 11-year activity cycle. But the Sun's activity is more complicated than this. Superimposed on the 11-year cycle is a much longer cycle that has produced a series of 24 'grand maxima' over the past 9,000 years. The latest grand maximum, which started in about 1920, is now coming to an end, so the next solar maximum, due in 2013 or 2014, should be unusually low (see 'Solar cycles').

These facts should not cause complacency, however. Although a solar maximum might bring a higher frequency of more intense storms on average, there is no evidence that these long-term trends affect the intensity of any individual burst of solar activity — indeed, the 1859 event occurred outside of a grand maximum. We need to develop safeguards against the entire range of possible events that can be generated by CMEs.

The first step towards this goal involves increasing the availability of data, so that statistical methods can be used to improve estimates of worst-case scenarios. A 2011 statistical study[3] of digital magnetometer data taken in northwest Europe since 1980, for example, looked at the intensity of an event that is likely to occur once every 200 years. For the short-time-frame magnetic field variations (in the order of minutes) that threaten power grids, the study estimated a worst-case intensity in the range of 1,000–6,000 nanoteslas per minute. Fortunately, this roughly matches the US and UK estimates of a worst case of 5,000 nanoteslas per minute, which was taken from one observation from central Sweden during the May 1921 event.

Most historical data sets exist only on paper as charts or tables, sometimes handwritten. These include ionospheric data going back 80 years and magnetic data going back 170 years. Over the past decade, much progress has been made in identifying these historical records; they now need to be made usable through digitization. The advent of web-based citizen-science projects may offer a way forward, with volunteers transcribing printed or handwritten values, or converting graphs to tables. This approach is already being used to analyse handwritten historical temperature records for climate-change studies. There is a large public appetite for this type of engagement, and such work can prove scientifically useful for space weather forecasting. In the Solar Stormwatch project, for example, volunteers measure features of CMEs in real time, and the measurements are then used to track and forecast the arrival of the eruptions at Earth.

"Geomagnetic storms pose a serious threat to our technology-dependent society."

A second important step to safeguarding against CMEs is developing physics-based modelling: models that are based on a fundamental understanding of CMEs, rather than relying solely on what has been seen before.

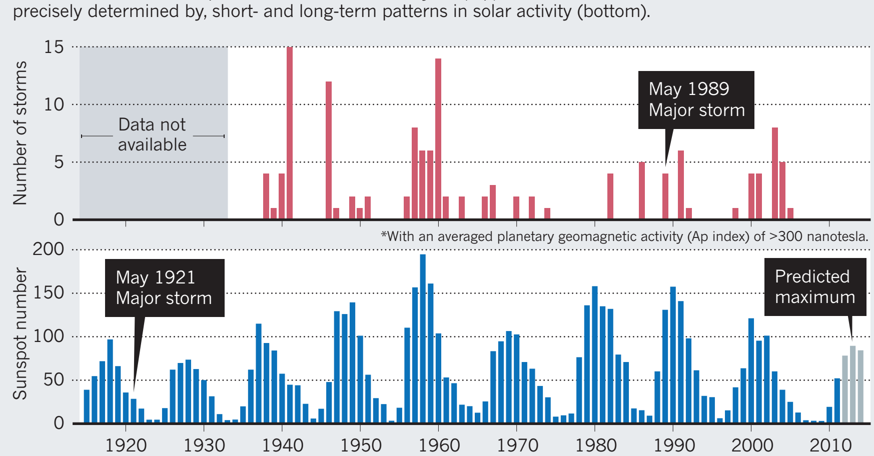
These models require an understanding of how CMEs travel through interplanetary space and inject energy into Earth's magnetosphere, and of how the resulting geomagnetic storm alters the composition, temperatures and velocities of the upper atmosphere. In this way, extreme events can be simulated before they happen. However, such modelling is still in its infancy, comparable with the situation in atmospheric modelling 50 years ago. Most efforts today focus on specific elements in the chain. A partnership established in 2011 between the NOAA and the UK Met Office — part of increasing UK–US collaboration on space weather — is aiming to build a more integrated, practical model for forecasting these events.

Models for space weather forecasts need to include long-term changes to Earth: its magnetic field has declined by 10% since 1850, and the height of upper atmospheric layers may be changing in response to climate change. Physicists need to learn how these factors will affect space weather, and that can be done only through good physics-based modelling.

The models are also limited by the complexity of some of the physics involved. For example, extreme space weather conditions create a strong flow of plasma of perhaps many kilometres per second in the ionosphere. For computational efficiency, models generally treat this plasma as a magnetized fluid in thermodynamic equilibrium. This simple description works well when modelling large-scale features, but it misses the rich set of plasma phenomena that arise during strong plasma flows. In these very energetic conditions, modellers should expect significant deviations from thermodynamic equilibrium. Physicists need to develop small-scale models that capture this full range of plasma physics, and then find computationally efficient ways to incorporate them into large-scale simulations.

SOLAR CYCLES

The number of severe* space weather storms each year (top) is related to, but not precisely determined by, short- and long-term patterns in solar activity (bottom).



SOURCE: SWPC/NOAA


R. S. BERTINUSSEN/SCANPIX/REUTERS

Space weather, which sometimes causes auroras on Earth, threatens to play havoc with electrical grids and to disrupt signals from the Global Positioning System.

A third, more speculative, way to safeguard against CMEs is to look at space weather around other stars. We can observe flares on other stars, for example, using X-ray space telescopes such as the European Space Agency's X-ray Multi-Mirror (XMM)-Newton. In the near future, we may also be able to observe radio and near-infrared emissions from auroras on gas-giant planets around those stars. That will give us insight into the power carried by their stellar winds, in particular by CMEs. To make a valid comparison with our own space weather, we will need to focus on Sun-like stars with similar rotation rates to the Sun. At present, this limits such studies to something between two and ten discovered stars. The search for such stars is already a hot topic in stellar astronomy, and should be encouraged as an area that has the potential to broaden our understanding of space weather.

FUNCTIONAL KNOWLEDGE

Alongside improvements to our knowledge of worst-case-scenarios, we must also ensure that crucial industries are prepared. The electrical power industry has a good awareness of the geomagnetic threat after the 1989 failure in Quebec. Power grids can and do harden their systems by installing transformers that are more resilient to power fluctuations, and by having enough reserve generators to weather a storm.

In aviation, severe space weather can black out communications links to the ground, disrupt on-board electronics and increase the radiation dose accumulated by aircrew and passengers. There is some awareness of these risks: airlines operating transpolar routes divert to longer routes at lower latitudes during bad space weather (incurring costs of extra fuel and crew hours). The US Federal Aviation Administration is supporting work to establish international standards for space weather forecasts for preflight briefings.

Further work will be needed for both industries as the worst-case scenarios become clearer. For example, the power sector will need to decide whether it is cost-effective to add expensive devices to power grids to block the extra currents generated by space weather, as has been done in Quebec. Right now, such discussions are not based on sufficient facts.

A less obvious risk is the potential loss of the accurate timing signals provided by GPS. Many industries exploit these signals: for example, the finance industry needs to time-stamp transactions with millisecond accuracy to support automated trading. This threat is easily overcome by using high-precision local clocks that require only occasional synchronization with GPS, perhaps once every few weeks. In this way, industries could survive a severe space weather event lasting one or two days. When I was preparing a report on solar storm impacts with Lloyd's insurance in 2010, it was unclear whether industries that rely on accurate timing are taking such steps. Private operators should be encouraged to be open about their efforts to safeguard against space weather.

National organizations that assess space weather risks include the UK Civil Contingencies Secretariat and the US Federal Emergency Management Agency. Several international bodies also have growing space weather efforts, including the World Meteorological Organization in Geneva, Switzerland, and the European Commission, the latter of which held a Space Weather Awareness Dialogue in October 2011. We should combine these efforts through an international network, bringing together all aspects of risk and implication assessments, operational responses and policy development.

This area of science has moved away from its roots in astronomy and communication engineering and is now better handled as a generic environmental risk to society and the economy, in parallel with earthquakes, volcanoes and floods. National and international funding organizations are increasingly transferring relevant funds to environmental research bodies. This is a welcome development that should be encouraged.

Geomagnetic storms pose a serious threat to our highly vulnerable, technology-dependent society. We need a much better understanding of the likelihood of space weather disruptions and their impacts, and we need to develop that knowledge quickly. ■

Mike Hapgood *is head of the space environment group with RAL Space, part of the UK Science and Technology Facilities Council. He is based at the Rutherford Appleton Laboratory (RAL) in Didcot, UK, and chairs an expert group that advises the UK government on space weather risks.*
e-mail: mike.hapgood@stfc.ac.uk

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