by Dawn Lenz

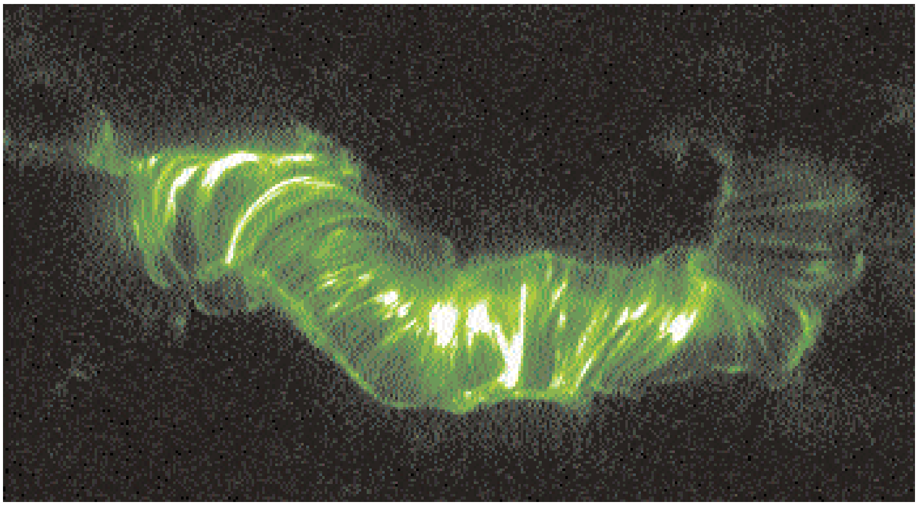
Understanding and Predicting Space Weather

The consistency on Earth of visible solar radiation belies the sun's dynamic and turbulent state. Just beneath the solar surface, or photosphere, a layer of ionized hydrogen (along with a little helium and traces of heavier elements) churns and mixes to a depth of about 200,000 km, convecting heat from the 15-million-kelvin core to the 5,800-K surface. The churning charged particles generate electromagnetic fields that blossom from the sun's surface in spectacular patterns, which are observed in the tenuous, 1-million-kelvin plasma of the solar corona. The corona forms the base of the solar wind, the continuous, even-more-tenuous stream of charged particles that flows outward from the sun into interplanetary space. The effects of the interaction of solar charged particles with Earth's magnetic field are referred to as space weather.

Like terrestrial weather, space weather is characterized by an average state of relative calm punctuated by bursts of activity. These solar storms vary in strength and frequency with the 11-year solar-activity cycle and cause disruptions of various magnitudes on Earth. During calm periods, the only manifestation of solar weather may be the auroras (Northern or Southern Lights), caused by the excitation of atmospheric oxygen and nitrogen by the solar wind's energetic electrons. Flares and coronal mass ejections (CMEs) are two types of solar eruptions that can spew vast quantities of radiation and charged particles into space, potentially causing geomagnetic storms. If a large flux of charged particles from the sun intersects the Earth, it can have serious consequences for modern support systems, including electrical power grids, communications networks, and satellite operations.

Flares and CMEs differ spatially and temporally. Flares are strong transient outbursts of radiation, released near the solar surface, that extend tens or hundreds of thousands of kilometers into the outer solar atmosphere (Figure 1). They are highly localized on the sun. Flares typically last for a few minutes to a few hours, and they emit radiation across most of the electromagnetic spectrum. Most of a flare's energy is released as radiation in the corona, but some energy contributes to forcing electrons and ions through the outer solar atmosphere and into the interplanetary solar wind.

CMEs are slower to develop (they emerge from the sun over the course of a few hours) and have spatial extents many times that of flares. Most of their energy is expended in driving ionized particles into interplanetary space rather than in radiation (Figure 2). The angular size of a CME can range from a few degrees up to half a solar hemisphere or more. If a flare is analogous to an interplanetary thunderstorm, a CME initiates an interplanetary tsunami—a flood of billions of tons of protons and electrons bursting from the sun that is capable of massive interference with any flux-sensitive apparatus it happens to encounter.



TRACE/Stanford-Lockheed Institute for Space Research

Figure 1. This false-color ultraviolet image of a flare shows a 50,000-km-wide arcade of magnetic structures released near the solar surface.

Solar storms on Earth

As technology advances, populations grow, and urban industrialized areas sprawl, Earth becomes more dependent upon systems that are vulnerable to damage from solar storms, including electrical grids and the swarm of satellites in orbit above Earth's protective atmosphere. Today's electrical grids are more susceptible to solar-storm disruption than their more localized predecessors because of the large geographical areas they cover and their interconnected nature (see *The Industrial Physicist*, October/November 2003, pp. 8–13). Communications systems and networks have developed beyond ground-based lines to satellite-based transmissions. Humans and their support systems venturing more extensively beyond the safety of Earth's atmosphere and into orbit, to the moon, or one day to the planets are largely unshielded from the solar storms that Earth's magnetosphere deflects at home (Figure 3).

Satellite-based activities and operations are also vulnerable to the direct impact of a flux of solar energetic particles. About 150 satellites currently orbit Earth hundreds to thousands of kilometers above the top of the atmosphere for the purpose of relaying television and telephone signals at very high to ultrahigh frequencies (VHF/UHF). Both frequency ranges are used because their short wavelengths can penetrate Earth's ionosphere with minimal reflectance and interference. However, VHF and UHF wavelengths are not short enough to afford them complete immunity to atmospheric interaction, and they are susceptible to disruption from significant modulations in the ionosphere, which can occur during solar storms. One such storm occurred on July 14, 2000, when a large flare bombarded

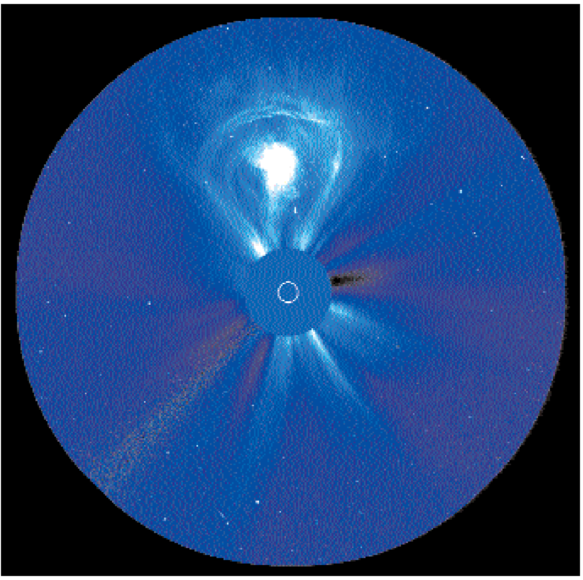

SOHO/LASCO (ESA and NASA)

Figure 2. This white-light image shows a coronal mass ejection exploding from the sun and extending about 10 million kilometers (the small white circle represents the sun, which is centered on the instrument's blocking disk).

Earth with energetic particles that disrupted communications and associated support systems. Weather satellites returned pictures blurred by static, commercial fishing boats lost radio communication, and power companies in the northeastern United States had to reroute electricity in response to voltage disruptions.

In addition to operational interference, satellites and power grids can suffer physical damage from solar storms. Satellites draw power from solar cells, which consist of semiconductor materials that are sensitive to energetic ions. The continual flux of solar particles gradually degrades the effectiveness of solar cells, eventually crippling the satellites when the cells can no longer generate the required power. Solar storms significantly accelerate such degeneration. A single strong solar storm can decrease the lifetime of a satellite's solar-cell system by several years.

Electromagnetic systems are vulnerable to electromagnetic-field fluctuations induced by a rapid influx of charged particles. Within power grids, geomagnetic storms can cause large-scale fluctuations and outages. Perhaps the most notorious solar-induced power outage occurred on March 13, 1989, in Quebec, when 6 million people experienced a 9-h electrical blackout caused by a CME. In addition to causing a loss of power, such events can damage power-grid hardware as abnormally large currents and voltages overload the system. Widespread power outages and communications breakdowns can cost millions of dollars; the 1989 Quebec outage cost an estimated $300 million. On a national scale, the economic impact of such an event can be in the billions of dollars.

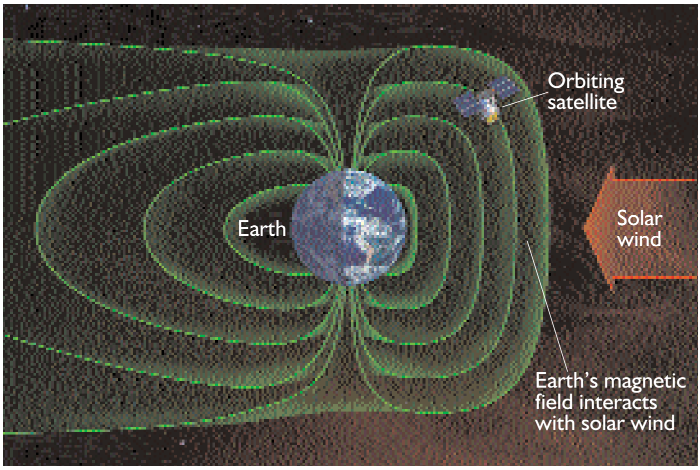


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Figure 3. The flux of charged particles in the solar wind interacts with Earth's magnetic field and can cause operational and physical damage to orbiting satellites.

Eruption physics

Our observational picture of solar flares and CMEs has improved dramatically over the last decade with the inception of state-of-the-art solar telescopes and satellite-borne instruments, such as the Solar and Heliospheric Observatory, the Transition Region and Coronal Explorer, and, most recently, the Ramaty High Energy Solar Spectroscopic Imager. However, the detailed underlying physical causes of solar storms largely remain a mystery.

Theories of how flares and CMEs develop and erupt, the conditions in the solar atmosphere required for the generation of such phenomena, and the mechanisms by which the energy is expelled and the particle flux is propelled outward into interplanetary space are areas of active investigation in solar physics. The foundation of almost all such theories involves the twisting and tangling of magnetic-field lines in the solar atmosphere as a result of the underlying fluid motions in the convective layer just beneath the solar photosphere. According to the theory of magnetic reconnection, developed by Eugene Parker of the University of Chicago and Peter Sweet of the University of Glasgow (Scotland) in the 1950s, solar magnetic-field lines progressively become more chaotically intertwined, increasing the stresses between them (Figure 4). When the stresses become severe enough, the field lines reconnect with an associated release of energy.

Flares and CMEs are sometimes observed to occur together. Until recently, this observation compelled researchers to look for a causal relationship between the two. Although both types of eruptions are believed to have physical roots in magnetic reconnection, solar physicists generally no longer envision a causal relationship and treat each separately in doing phenomenological modeling. Similarly, solar physicists believed for decades that flares caused geomagnetic storms. Such a correlation seemed plausible, given the enormous energy fluxes observed in flares, and solar-terrestrial storms do sometimes appear to be correlated with solar flares. However, explaining the physical correlation proved to be a challenge because there are both temporal and spatial inconsistencies between flares and geomagnetic storms. Flares typically last for at most a few hours and are highly localized. Storms can last for days and cover many times the area of flares.

The key player in major solar-terrestrial events is now thought to be the CME rather than the flare. CMEs went unrecognized as significant solar phenomena for many decades after flares first received close attention, in part because CMEs produce less radiation than flares and require more sensitive and careful observation. Rather than expelling energy predom-

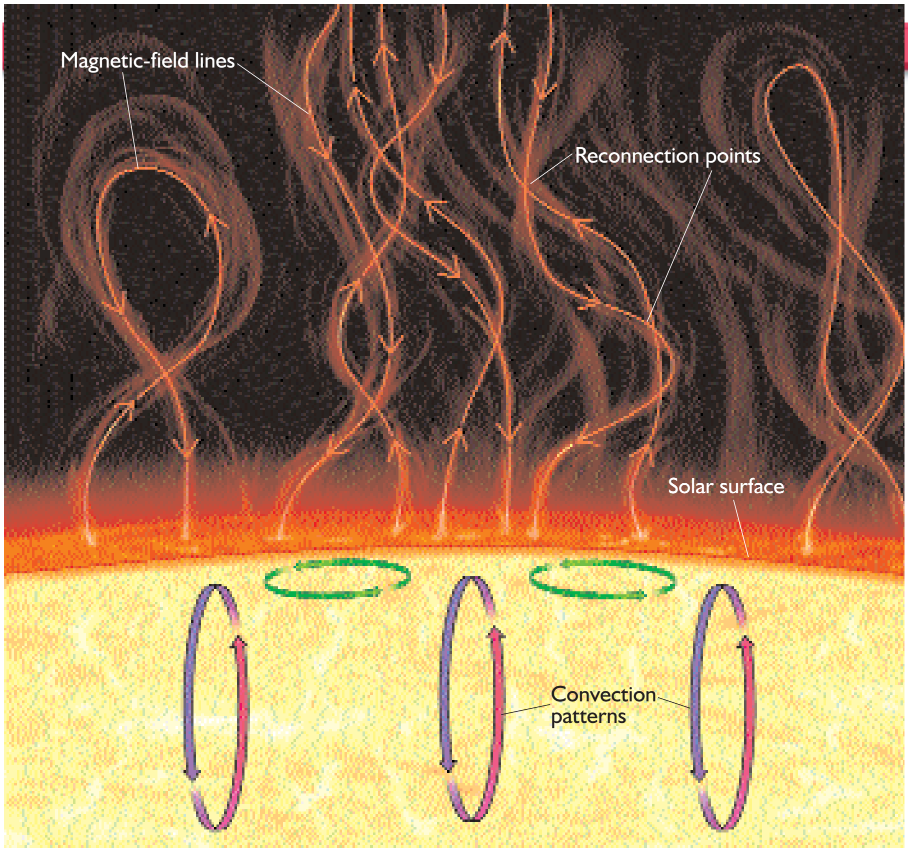

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Figure 4. Solar magnetic-field lines, anchored in the turbulent convective zone beneath the surface, become tangled and braided. The associated buildup of magnetic stress triggers reconnection, in which the field reverts to a topologically simpler state via release of the stored energy.

inantly in the form of radiation and localized particle acceleration, a CME uses its energy to propel ions and electrons into interplanetary space.

Currently, the generally accepted model of the largest solar-terrestrial events is that they are caused by the acceleration of interplanetary charged particles ahead of a CME-induced shock. The triggers of CMEs, however, remain under debate as scientists pursue observational data to test various theories. Two competing views are (1) CMEs are triggered by the twisting and subsequent reconnecting of magnetic-flux ropes beneath the solar surface, with the released energy forcing particles out from inside the sun, and (2) CMEs, like flares, are triggered by the release of magnetic energy in the corona, above the solar surface (Figure 5).

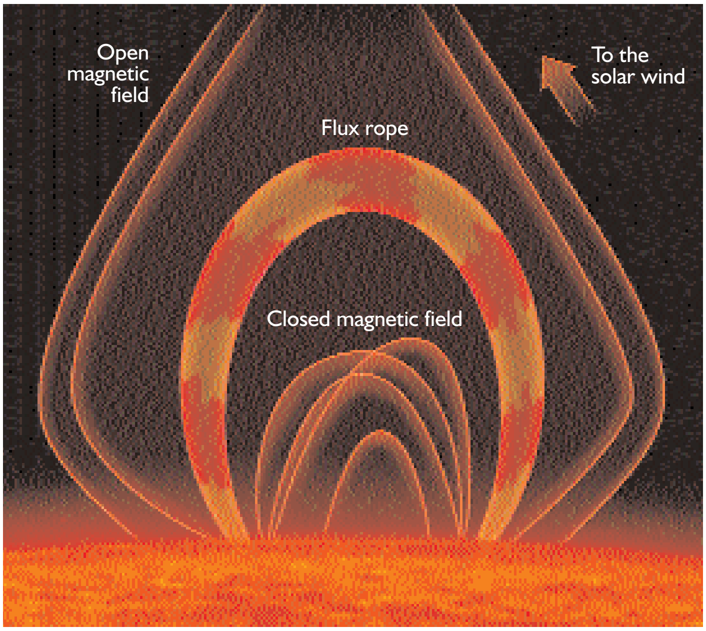

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Figure 5. The solar magnetic field consists of both "closed-field" and "open-field" regions. Coronal mass ejections are thought to involve the evolution of field between closed and open configurations. Flux ropes—twisted bundles of magnetic-field lines—are believed to be part of the precursor field configuration.

Predicting storms

The peak of the last 11-year solar cycle, with a corresponding peak in flare and CME events, was in 2000, when Earth was significantly more dependent on power grids and satellite-based communication than during the previous peak. This dependency, coupled with new knowledge about the causes and effects of solar storms, spurred efforts to predict large geomagnetic storms in hopes of mitigating their effects.

As in meteorology, the tools of space-weather forecasting include observations and model predictions. Observational data include in situ measurements of radiation and energetic particles at satellite orbit altitudes, and ground-based magnetometer data. In addition, solar-physics research satellites can provide data on current conditions at the sun. However, their instruments collect high-resolution data of just a few percent of the solar disk at a time, so only events occurring in the field of view for a specific observation sequence are captured. Space-weather modeling aims to take observational data as input and help forecasters predict storms. This relatively new field has grown significantly in recent years; about 70% of the existing academic literature on space-weather modeling has been published since 2000. As interest in space-weather prediction increases, the models continue to improve.

Satellites designed for space-weather exploration include Wind (launched in 1994), the Advanced Composition Explorer (1997), and the Imager for Magnetopause-to-Aurora Global Exploration (2000). Their instruments gather radiation and particulate data to discover the characteristics of the interaction between the solar wind, solar energetic particles, and Earth's magnetosphere. On Earth, networks of ground-based magnetometers detect fluctuations in the planet's magnetic field. Solar storms commonly induce fluctuations on the order of 1% in the measured magnetic field; magnetometers can detect fluctuations several orders of magnitude smaller. Together, satellite and magnetometer data can provide accurate, up-to-the-minute space weather forecasting.

The first commercial space-weather prediction system was installed in England in January 2000. SpaceCast/PowerCast, developed by the Metatech Corp. (Goleta, CA), collects up-to-the-minute data from a group of satellites and networks of ground-based magnetometers about the sun's radiation and magnetic-activity levels. Predictive modeling is coupled with observational data to create specific regional forecasts. The system provides advance warning of an impending solar storm, permitting crucial or sensitive power-grid components to be shut down or otherwise protected. Devices that block anomalous currents are expensive to install on a large scale, however, so disabling essential components is currently the most cost-effective way to prevent damage.

As with severe terrestrial storms, the effects of solar storms can be mitigated with accurate and expeditious forecasting. The ability to predict major solar storms can give power companies sufficient lead time to implement preventive measures. Like sandbagging and nailing boards over windows before a hurricane, contingency strategies cannot disarm a major geomagnetic event, but they can significantly lessen its impact. Advance warning of storms can also, in principle, allow communications companies to notify their customers that a lapse in service may be imminent and estimate how long the lapse might last.

Our understanding of both the causes and the terrestrial effects of space weather is a subject of active research. Industrial focus on geomagnetic storms has thus far been motivated by efforts to reduce their impact, but just as we have learned to capture solar radiation and wind energy for modern power applications, we may one day learn to lasso and exploit the energy that reaches us in solar storms.

Further reading

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Golub, L.; Pasachoff, J. M. *Nearest Star: The Surprising Science of Our Sun*; Harvard University Press: Cambridge, MA, 2001; 267 pp.

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Parker, E. N. *Interplanetary Dynamical Processes*; Interscience Publishers: New York, 1963; 272 pp.

Space-weather forecasts and more information about space weather are available from the Space Environment Center of the National Oceanic and Atmospheric Administration at http://www.sec.noaa.gov, and the Canadian Space Weather Forecast Centre at http://www.spaceweather.gc.ca.

BIOGRAPHY

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