Killer Sun?

The Sun, a seething ball of nuclear fusion and magnetic fields, occasionally hurls exceptionally powerful radiation and charged particles into interplanetary space. Woe to any unprotected high-tech electronics in the way ...

By: ***Trudy E. Bell, M.A.*** text ©2025 Trudy E. Bell

Shortly before noon on September 1, 1859, in Redhill, Surrey, near London, experienced British solar observer Richard Carrington was finishing his hand drawing of an unusually large group of sunspots when he saw "two patches of intensely bright and white light" break out amid the darker spots, with a brilliance "fully equal to that of direct sun-light." Flustered by the unexpected sighting, he "hastily ran to call someone else to witness the exhibition with me;" returning in less than a minute, Carrington was "mortified to find that it was already much changed and enfeebled" and soon gone altogether. The entire freak phenomenon had lasted under five minutes.

By lucky happenstance, another solar observer, Richard Hodgson, in a nearby London suburb of Highgate, had been making his own sunspot drawing at the same time. Independently, he was dazzled by "a very brilliant star of light, much brighter than the Sun's surface" among the same group of sunspots. Duration: about five minutes.[1]

But that was only the beginning. At the Kew Gardens Observatory in London, a new instrument called a self-recording magnetograph, built to photographically monitor fluctuations in Earth's geomagnetic field, recorded a "crotchet" or "crochet"— a hook-shaped glitch or excursion of the recording pen — at the time Carrington and Hodgson noted their perplexing transient brilliant "star" on the Sun.[2]

Seventeen hours later — around 4 a.m. Greenwich time on September 2, 1859, — multicolored auroras or "Northern Lights" so brilliant one could read newspaper print began dancing luridly across the dark night skies, extending south of Caribbean latitudes. Simultaneously, in telegraph offices across Britain and the United States, communications were interrupted as equipment overheated and leaping sparks scorched paper and wood, shocking operators and setting fires. The operators scrambled to disconnect the telegraph wires from the phalanxes of chemical batteries that powered them (1859 being decades before centralized distribution of electrical power).

Even so, telegraph offices miles apart recorded huge phantom currents surging through the disconnected wires, even allowing fitful signals to be transmitted among the astounded operators.[3]

Carrington and several other astronomers on both sides of the Atlantic strongly suspected that all the coinciding bizarre phenomena on Earth were somehow related to one another as well as to the earlier startling appearances witnessed on the Sun. Over succeeding decades, they were proven correct (recognizing that visible light and other wavelengths of electromagnetic radiation travel at the speed of light, everything else taking hours or days). Thus, dramatically were born the scientific fields of solar physics and space weather, the physics of the Sun-Earth connection.

Today, an increasing number of engineers are realizing the hazards another Carrington-sized event on the Sun could pose to the ubiquitous precision electrical and electronic assets that our 21st-century high-tech society takes for granted, both on the ground and in space.

Page 6 image: The Aurora Borealis in the starry sky in the tundra, just below the ice caps of the Arctic. Image Credit: Denis Sergeeich.

WHAT WAS THE CARRINGTON-HODGSON EVENT?

Carrington and Hodgson are now credited with being the first to have observed a white light solar flare — and not just any old solar flare, but perhaps the largest and most energetic solar flare in modern recorded history.

A solar flare is a sudden release of electromagnetic radiation associated with sunspots. Most commonly, solar flares are observed at ultraviolet or X-ray wavelengths. Rare ones, such as the Carrington-Hodgson event, also can be seen at visible wavelengths; they are particularly energetic white light solar flares.

Solar flare strengths are categorized by their peak brightness at X-ray wavelengths into a logarithmic scale of five letters (A, B, C, M, X), where each letter represents an energy output 10 times greater than its predecessor: A-class solar flares are near background levels, B-class are 10 times greater, etc. The most powerful flares are X-class: the largest explosions in the solar system, releasing energy equivalent to over a billion hydrogen bombs in a matter of seconds.

X-class solar flares can trigger global radio blackouts on Earth and long-lasting radiation storms in the ionosphere — the charged layer of Earth's upper atmosphere some 50 to 400 miles up that modifies and reflects radio waves. The magnetic crotchet recorded at Kew in 1859 indicated the presence of just such an ionospheric disturbance, now called a "solar flare effect" (SFE), caused by extra ionization from extreme ultraviolet and X-ray radiation.

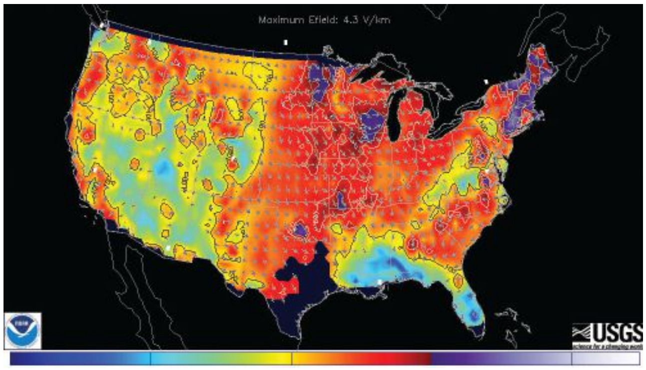


Figure 2: Across the United States on May 10 and 11, 2024, as colorful auroras danced overhead, strong electrical currents were also surging through rocks and soil. The biggest voltages along the U.S. Eastern Seaboard and in the Midwest were as much as 10,000 times normal. The May 2024 storm was, electrically speaking, about half as intense as the storm that blacked out Québec in 1989. The map is a snapshot of a real-time display of electric voltages in the ground, derived from a database of electrical conductivity of the ground, and observed disturbances of the Earth's magnetic field. Absent such activity, the map would be mostly blue. Credit: NOAA/USGS.

Within each letter class, solar flare energies are more finely divided on a scale from 1 to 9, although for X-class flares the numbers can go much higher than 9. The Carrington-Hodgson white light flare has been estimated to have been in the range of X45 to X64.4.[4] For recent comparison, the two big solar flares of last year (May 10 and 11, 2024) that caused dramatic auroras to be sighted even south of Mexico City were rated "only" X5.8 and X1.5.[5]

Flares are often, but not always, associated with coronal mass ejections (CMEs): expulsions of gigantic bubbles of solar matter threaded with magnetic field lines, which spew electrons, protons, and heavier charged particles out into the solar system. Unlike electromagnetic radiation, which travels in a straight line, the charged particles follow a spiral path of twisted magnetic fields rooted in the Sun. If a major CME happens to be ejected on a path toward Earth, its energetic solar particles can cause not only beautiful auroras in the ionosphere; they also can damage electronics on Earth or in space, and potentially harm astronauts in orbit or even passengers in high-flying aircraft.

Such a blast of fast solar charged particles can also temporarily deform the Earth's magnetic field, causing compass directions to be unreliable. Electrical currents can be induced to flow through the Earth itself, causing spikes of energy in long power transmission lines, which can damage transformers and trigger electrical power outages.[6a]

That is what happened during a powerful geomagnetic storm on March 13, 1989, when in less than 90 seconds the 21,000-megawatt Hydro Québec power grid collapsed, plunging the entire province of Québec and parts of the Northeastern U.S. into darkness for nine hours.[7] Fluctuations in the Earth's magnetic field can disrupt directional drilling operations for oil and gas, which rely on magnetic sensors near the drill bit to control its accurate position and orientation.[8] Strong magnetic fluctuations can also cause electrical corrosion of pipelines (which are essentially long wires as far as nature is concerned), and warp transformers with high currents.

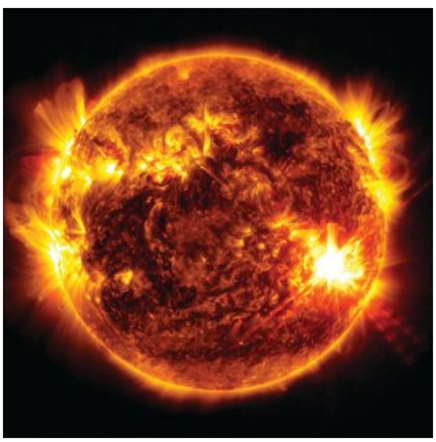


Figure 1: Last year, on May 11, 2024, a large sunspot cluster produced several strong flares (one appears as the white spot to the lower right) and also coronal mass ejections (CMEs). As the CMEs reached Earth, they triggered a severe to extreme geomagnetic storm, one of the most powerful in over two decades. The National Oceanic and Atmospheric Administration (NOAA) coordinated with operators of power grids, satellites, and navigation systems to take protective actions against the induced currents from fluctuating magnetic fields, to prevent blackouts or damage to infrastructure.

Credit: NASA Solar Dynamics Observatory.

Geomagnetic storms resulting from CMEs are categorized by their own three-tier Space Weather Scale devised by the Space Weather Prediction Center (Boulder, CO) of the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS). The lowest level is Radio Blackouts or R; an intermediate level is Solar Radiation Storms or S; the most disruptive level is Geomagnetic Storms or G. Each level R, S, G is numerically divided into five intensities (1 through 5, for minor, moderate, strong, major, extreme).

Although a widespread power blackout could cause internet and cell phone service outages, the actual likelihood of a potential much-ballyhooed "internet apocalypse" directly due to solar activity is believed to be at least somewhat exaggerated in popular media. Cell phones operate on high frequencies not significantly affected by ionospheric disturbances — that is, as long as the cell phone towers have power. To ascertain the actual odds, however, in 2023 George Mason University and the Naval Research Laboratory received a five-year federal grant to study solar activity and its actual effects on electronic technologies.[6b]

BUT WAIT, THERE'S MORE

Carrington and Hodgson may have documented the first or biggest white light solar flare in recorded history, but 1859 was not the most recent time the Sun has produced a flare of comparable magnitude.

In early August 1972, a series of solar flares (including two rare white light solar flares) were followed 14.6 hours later by a "punishing" flux of solar energetic particles so intense that it saturated the particle detectors and caused at least one defense communications satellite to fail. Geomagnetically induced currents in the Earth disrupted both electric power from Manitoba Hydro Co. to Minnesota, and communications through long-distance AT&T cables in Illinois and Indiana.

Most freakish and dangerous (1972 being late in the Vietnam war), strong magnetic perturbations triggered the near-simultaneous detonation of some 4,000 magnetic-influence sea mines in a U.S.-sown minefield off Hon La, North Vietnam. The 1972 solar storm is now viewed as a "near miss" of a Carrington-scale CME.[9] Moreover, the flares happened between Apollo 16 and 17, the two last manned lunar missions. Had the flares occurred while astronauts were on the Moon, the crews would have been sickened from the intense radiation.

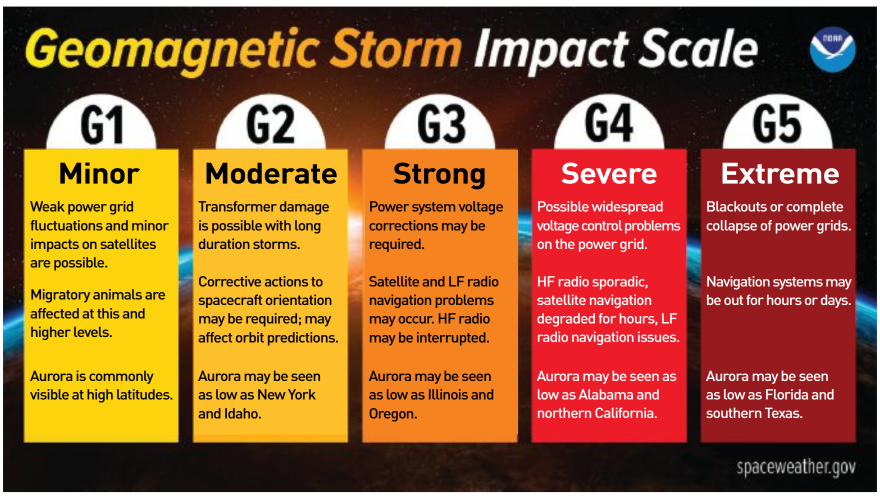


Figure 3: NOAA's Space Weather Prediction Center has introduced three space weather scales to describe the environmental disturbances for three types of events: geomagnetic storms (G, shown here), solar radiation storms (S), and radio blackouts (R). The scales have numbered levels that convey severity, analogous to scales for ranking hurricanes, tornadoes, and earthquakes.
Credit: *Spaceweather.gov*.

Carrington-scale flares are not even the most energetic explosions the Sun can produce. Since elementary school, many students have been taught that — fortunately for life on Earth — our beneficent Sun is a middle-aged, stable (so-called "main sequence"), quiescent, medium-sized yellow star (spectral class G2), ho-hum, despite its roughly 11-year sunspot cycle. Sure, compared to fast-burning hot blue giant stars or explosive novae or supernovae, the Sun is quiescent. But quiet is relative.

The now-defunct Sun-orbiting Kepler space telescope was launched in 2009 to look for earth-like planets around sun-like stars (spectral classes F8 to G8, that is, ranging from slightly warmer to slightly cooler than the Sun). Recent analysis of Kepler data from more than 50,000 sun-like stars reveals that statistically, approximately once a century, 5 percent of such stars emit rare "superflares" some 10,000 times more energetic than typical solar flares.[10] Evidence is yet inconclusive whether our Sun has done the same in the past (although statistically it seems that superflare stars may be younger than the Sun and rotate significantly faster than our Sun's 28-day period).[11]

However, in 2012, a then-grad student Fuso Miyake in Japan identified a spike in radiocarbon (carbon-14) concentrations in tree rings dating to 774–775 A.D. Her findings have since been confirmed by measurements of tree rings in other parts of the world, as well as spikes in concentrations of beryllium-10 and chlorine-36 for the same years in Antarctic ice cores.[12] The evidence suggests that every few centuries or millennia, the Sun has blasted forth a particularly scalding storm of solar energetic protons (SEP).

Half a dozen such powerful Miyake events (as they are now called) have been identified as having occurred over the past 5,000 years, including as recently as 993–994 A.D., shortly before Vikings arrived in the New World. Calculations imply that the 774–775 A.D. Miyake event would have had an estimated energy equivalent to a range of X284 to X410[13] — far more powerful than any old Carrington-Hodgson flare.

NO RESPITE

Lest one be lulled into complacency by the statistical rarity of such potentially devastating solar explosions, consider that flares and CMEs are far less powerful — and statistically far more common — than any Carrington-Hodgson event (much less a Miyake event) have already wreaked widespread temporary havoc on terrestrial and space-based engineered structures and high-tech services multiple times just in the Space Age.

Although well shy of Carrington-Hodgson energy levels, last year (2024) the May 10 solar flares triggered a 40-hour geomagnetic storm in the ionosphere that briefly reached the "extreme" class (G5).[14] Indeed, ionospheric disturbances were great enough to distort the timing of signals received on Earth from the 24 Global Positioning System (GPS) satellites. The cause is a phenomenon called ionospheric scintillation, somewhat analogous to the twinkling of stars at visible wavelengths. The irregular timing delays make the satellites appear slightly farther away or their positions uncertain, degrading the received GPS signals' navigational accuracy.

One down-to-Earth consequence in 2024 was that modern farm tractors, which rely on GPS signals of centimeter precision for precise directional plowing, planting, and harvesting, were idled in their fields right in the middle of spring planting season, when any delay could result in lower yields and less revenue.[15] Another consequence: during the "Halloween" geomagnetic storm of late October 2003, severe ionospheric scintillation of GPS signals compelled the Federal Aviation Administration (FAA) to disable its vertical navigation service (which enables close vertical separation of aircraft in flight) for some 30 hours to ensure that passenger safety was not compromised.[16]

Worse, even relatively weak solar activity can pose real-world risks to high-tech systems, as the company SpaceX discovered the hard way three years ago.

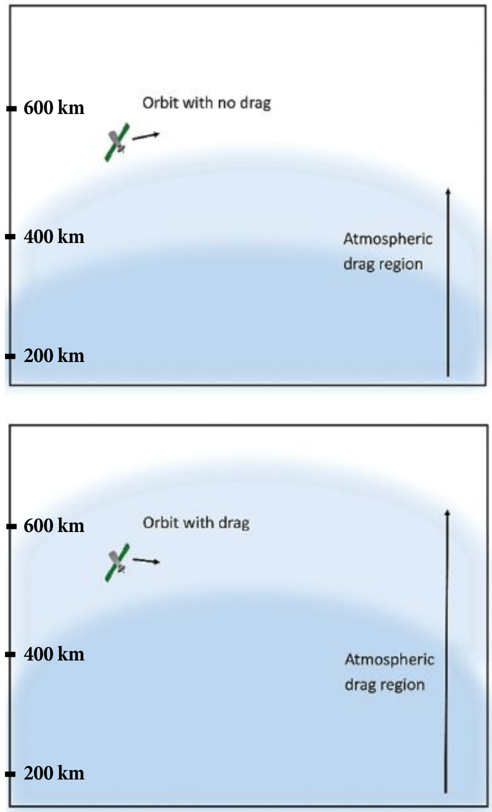
Low Earth orbit is not a perfect vacuum. Satellites orbiting between about 80 to 700 km (~50 to 400 miles) altitude are actually in Earth's "thermosphere," a rarefied upper part of the ionosphere where air molecules are photoionized by solar ultraviolet radiation. An influx of energetic charged solar particles can cause the thermosphere to heat up and expand, increasing atmospheric density at higher altitudes. That, in turn, increases atmospheric resistance (drag) on satellites in low Earth orbit, causing them to lose altitude. [**see Fig. 4a/b**] [17]

Such additional drag can be significant even during a moderate geomagnetic storm. On February 3, 2022, SpaceX launched 49 Starlink communications satellites into an elongated low staging orbit (210 km x 350 km) in preparation to being boosted to their higher (~550 km) operational circular orbits. Over the next four days, however, 38 of the Starlink satellites ended up deorbiting and spiraling back to Earth, a multi-million-dollar loss. Unexpectedly, atmospheric drag was an estimated 50 percent greater than what had been predicted for a mild geomagnetic storm (G1) produced by several moderate (M1.1 class) solar flares.[18]

THE NOT-SO-QUIET SUN

Even near or during sunspot minimum — the few years every solar cycle when the surface of the Sun appears nearly unblemished and magnetic storms seem to have subsided — there is no respite for sensitive electronics in space. Especially during the declining phase of the sunspot cycle approaching solar minimum, relatively cool "holes" open in the Sun's corona (its tenuous outermost atmosphere, visible as a silvery halo around the black disk of the Moon during the few minutes of totality in a total solar eclipse). In ultraviolet or soft X-ray images of the Sun, coronal holes look like vast dark areas [**see Fig. 5**].

Physically, coronal holes are locations primarily near the Sun's poles where the Sun's magnetic field lines do not close back on themselves as loops; instead, the magnetic field lines are open to interplanetary space, propelling the charged particles of the solar wind outward to speeds exceeding 500 to 1,000 km/sec. Coronal holes can persist for months (several solar rotations).



Figures 4a/b: Atmospheric drag has a significant impact on spacecraft in low Earth orbit (LEO), generally defined as an orbit below an altitude of approximately 2,000 kilometers (1,200 mi). Although the air density is low, air resistance in those layers of the atmosphere in LEO is still strong enough to produce drag and pull satellites closer to the Earth. The drag force on satellites increases when the Sun is active; at solar maximum, satellites may have to be maneuvered every two or three weeks to maintain their orbit. Credit: Trudy E. Bell/Allan W. Meyer/NASA.

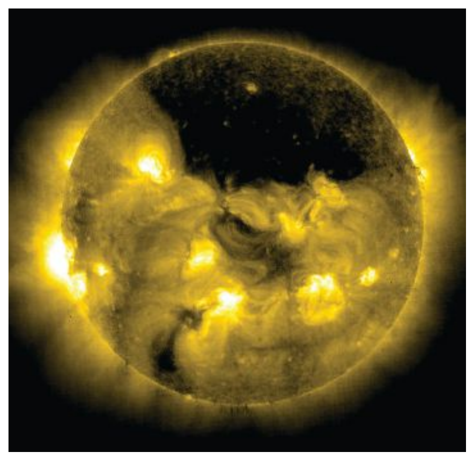


Figure 5: The European Space Agency/NASA Solar and Heliospheric Observatory (SOHO) captured this image of a gigantic coronal hole hovering over the Sun's north pole on July 18, 2013, at 9:06 a.m. EDT. The image was taken at extreme ultraviolet wavelengths, which highlight hotter solar material, so the colder coronal hole stands out in dark relief.
Credit: ESA and NASA.

When the solar wind meets Earth's magnetic field, the particles are deflected, either away from the neighborhood altogether or into one of the planet's two equatorially concentric ring-shaped Van Allen radiation belts [**Fig. 6**]. The inner belt (roughly 640 to 6,400 km high, although sources for numbers differ) is primarily made of protons originating from both the Sun and cosmic rays, and the outer belt (some 13,000 to 45,000 km high) primarily of solar wind electrons. Between the two radiation belts is a comparatively narrow slot or gap relatively clear of charged particles.

Once trapped in the outer radiation belt, energetic electrons can be accelerated to velocities well over half the speed of light, becoming so-called "killer electrons." Although the radiation belts protect Earth's atmosphere and life forms from destruction, relativistic killer electrons circulating in the outer radiation belt can damage spacecraft in medium Earth orbit (including GPS satellites) or in geostationary orbit (including communication satellites). Specifically, in the words of a recent study, the electrons can:

> penetrate satellite surfaces and embed themselves in insulating materials and ungrounded conductors. The charge can accumulate over time resulting in the build up of high electric fields in and between materials to breakdown levels… . The subsequent discharge can cause phantom commands, logic errors, erroneous data, loss of functionality and, in exceptional cases, serious harm to a satellite. [19]

For this reason, some medium Earth orbit satellites are inserted into orbits in the safer slot region to minimize time spent in either radiation belt. Others have no choice. GPS satellites, for example, must be at a specific altitude for the intended half-day orbits needed to maintain the 24-satellite constellation.

As already described, CMEs are one principal driver of geomagnetic storms, principally the greatest storms around solar maximum. However, coronal holes and their associated fast solar winds are the second big driver, principally causing weak to moderate geomagnetic storms around solar minimum (although CMEs, coronal holes, and other phenomena can occur at any point during the solar cycle).

Indeed, 30 of the 50 largest relativistic "killer" electron flux events over the past 20 years have been triggered by coronal holes, not by CMEs. That correlation and frequency has made some researchers wonder whether "satellites in GPS and geosynchronous orbit could be more at risk during a milder solar storm than from an extreme storm."[20]

HOW TO PREPARE?

The Sun is now approaching or in solar maximum for the current cycle (called solar cycle 25), which is predicted to last through 2025 and into 2026. Are our civilian and military technologies ready with adequate defenses? The insurance industry thinks not. "A solar storm of the same magnitude of the Carrington Event hitting Earth is inevitable as historical records indicate that extreme storms of that magnitude occur every 150 years," wrote cybersecurity expert David Piesse. "The total economic cost of such an event is estimated between $600 billion to $2.6 trillion" if outages are long-lasting and widespread enough to cause "a domino effect on human society." [21]

Over the past two decades, alert systems have been set up to warn power utilities and others of powerful CMEs heading for Earth, and to forecast solar wind parameters up to a week in advance. Examples include the U.S. NOAA/NWS Space Weather Prediction Center (*https://spaceweather.gov*) and the highly readable commercial daily service Space-Weather.com (*https://spaceweather.com*), and apps tied into them.

But there is much about the Sun and Earth that physicists and engineers do not yet understand well enough to be able to predict all potentially damaging space weather effects — and their consequences. "Only by developing our understanding of the dynamics of the Sun … will we really be able to forecast space weather events with any certainty," asserted meteorologist Simon Machin, manager of the U.K.'s Met Office Space Weather Programme.[22]

Fundamental scientific and technical questions include: what are details of the internal dynamics of the Sun and how do they cause solar cycles? Can we know the Sun's innards well enough to offer useful predictions — and warnings — about the Sun's behavior? Although empirical models exist of Earth's atmosphere and its responses to happenings on the Sun, can atmospheric drag and other factors be modeled with useful precision? How much shielding and other protections are enough to protect assets and people in orbit for various mission durations? How can findings be readily and regularly exchanged among scientific investigators and engineers domestically and internationally?

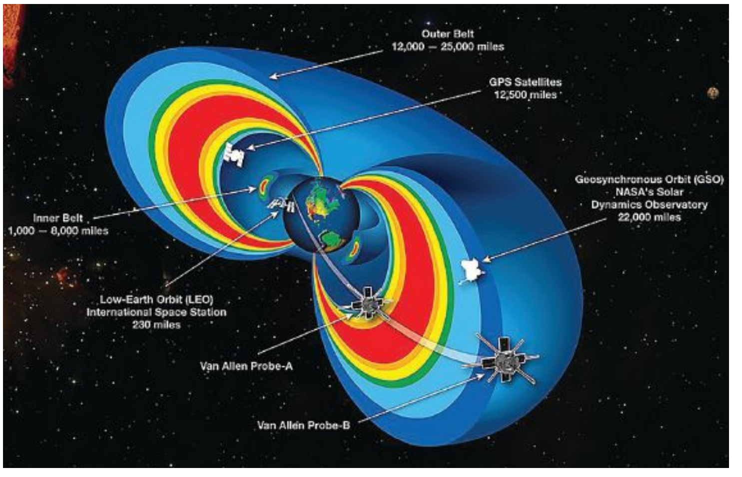


Figure 6: The Van Allen radiation belts are two donut-shaped regions encircling Earth where high-energy solar particles, mostly electrons and ions, are trapped by Earth's magnetic field. The energetic particles can affect the performance and reliability of technologies and pose a threat to astronauts and spacecraft. Also shown are a few satellites whose orbits take them through or near the radiation belts. Credit: NASA.

Over the past decade, a growing number of white papers have laid out the urgent need for greater expertise and/or plans for predicting and mitigating space weather effects.[23] Given society's increasing demand for — and reliance on — electrical and electronic goods and services ranging from global financial transactions, robotic surgery, electric vehicles, and cryptocurrency to military surveillance, autonomous cars, streaming entertainment, and artificial intelligence, many experts urge greater concrete action to adequately protect against outages.

Gratitude for manuscript comments is expressed to Dave Dooling (retired education officer at the National Solar Observatory and retired education director of the New Mexico Museum of Space History), Allan W. Meyer (retired staff scientist, NASA Ames airborne observatories KAO and SOFIA), and Sara Meyer (Senior Technician, University of Oregon Hazards Laboratory).

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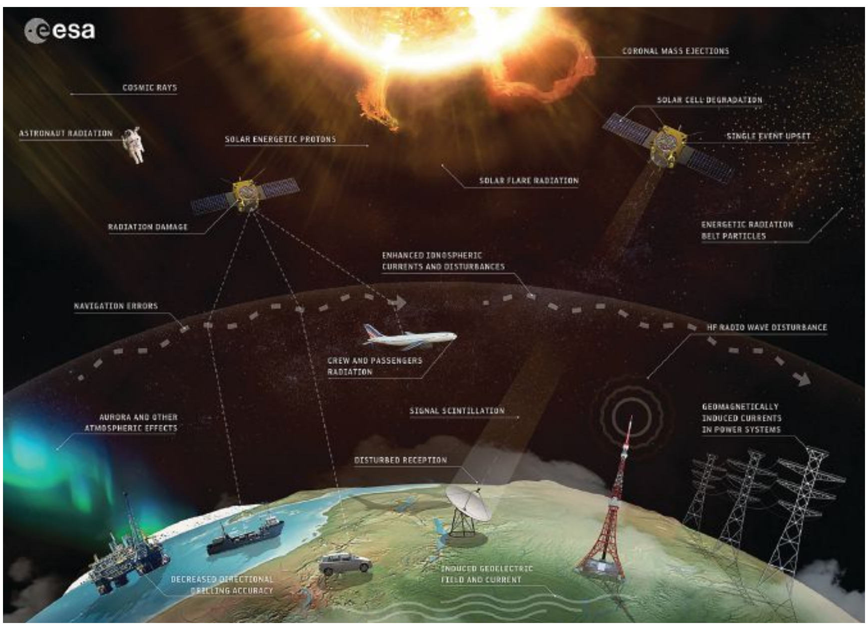
Selected References listed on page 45.

Figure 7: On December 7, 2023, representatives from NASA, NOAA, the National Science Foundation, and the Air Force signed a Memorandum of Agreement for a Space Weather Research-To-Operations-To-Research Collaboration to improve U.S. forecasts and services to mitigate the effects of space weather.
Credit: Bob Hyatt, NOAA.



THE SOLAR DYNAMO

The Sun is made up of plasma—an ultrahot dense mass of charged subatomic particles. Through convection, solar plasma circulates from interior to surface; it also moves from equator to pole, and faster at the equator than near the poles. Together, the movements generate magnetic fields that emerge from the Sun to form spots, coronal loops, and prominences, as well as giving the Sun an overall north-south magnetic polarity. This combination of moving charges contorts, collapses, and ultimately flips or reverses the Sun's magnetic field.

Centuries ago, astronomers studying the Sun first saw the number of sunspots wax and wane roughly every 11 years. But each visible sunspot cycle is actually just half of a 22-year magnetic cycle, now called the Hale cycle, when the magnetic field flips and then returns to its original polarity. For reasons still unknown, every few centuries the solar magnetic cycle all but disappears (as happened during the Maunder Minimum, 1645–1715, about three Hale cycles) or enhances (such as Modern Maximum, 1914–2008, about four cycles).

The Sun's magnetic cycle can impact Earth. Basic electromagnetic theory teaches that given magnetism, electricity, and force, any two produce the third. Magnetism moving across a conductor produces electricity, the basis of generators. A spike in magnetic intensity spikes the current. A coronal mass ejection squeezing Earth's magnetic field in space induces strong electric currents along wires and pipelines on the ground, one form of electromagnetic pulse (EMP), which can impair or destroy electrical infrastructure through arcing and heating. Other forms of EMP can be produced by lightning and high-altitude nuclear blasts.

– Dave Dooling and TEB

Figure 8 (left): Space weather effects on the ground can include damage and disruption to power distribution networks, increased pipeline corrosion, and degradation of radio communications.
Credit: European Space Agency.

Killer Sun? Continued from page 11.

Selected references: (Due to space limitations, many URLs are not included)

The first six-episode season of the British political thriller TV series *COBRA*, released in 2020 by Sky One, explores possible societal reaction to the prolonged outage of the U.K. power grid by a powerful solar flare and resultant CME and EMP.

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