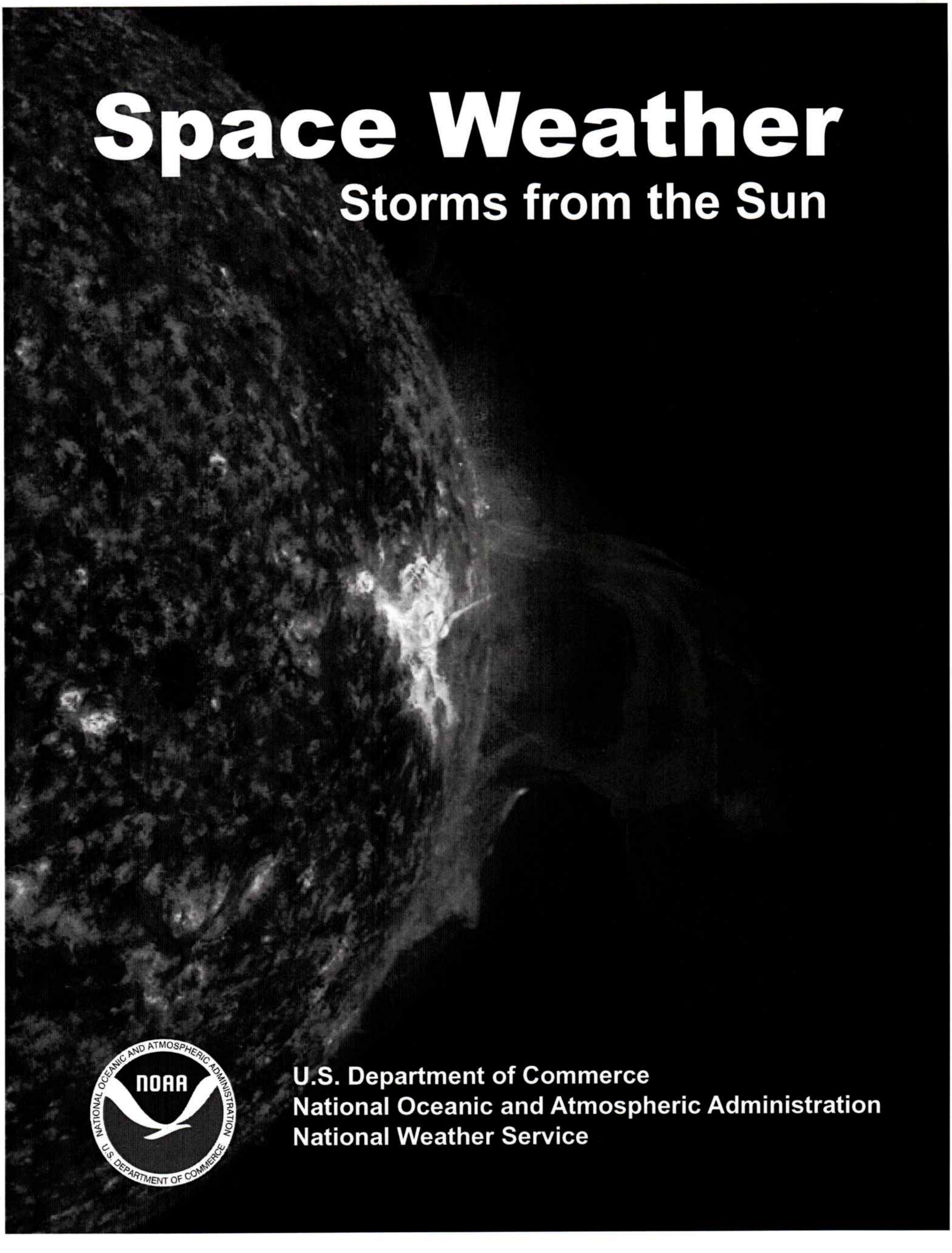
Space Weather

Storms from the Sun



U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service

A dramatic example of the effects of space weather occurred in March 1989 when a solar storm knocked out power in Quebec for up to 36 hours. The Hydro-Quebec electrical utility went from full operating capacity to blackout status in 92 seconds. Six million people were plunged into cold and darkness.

WHAT IS SPACE WEATHER?

Activity on the Sun can cause space weather storms that affect us here on Earth. Solar storms can impact the technology we rely on everyday: Global Positioning Systems (GPS), satellites, and electric power grids. Just as with other types of weather, the National Weather Service forecasts space weather disturbances and serves as the official source for civilian alerts and warnings.

Space weather is a consequence of the behavior of the Sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system. There are various phenomena that originate from the Sun that can result in space weather storms. Outbursts from huge explosions on the Sun—Solar Flares and Coronal Mass Ejections (CME)—send space weather storms hurling outward through our solar system. The Sun also emits a continuous stream of radiation in the form of charged particles that make up the plasma of the solar wind.

Solar Particle Events

release large numbers of high energy charged particles, predominately protons and electrons, which are accelerated to large fractions of the speed of light. These particles may arrive at Earth between 30 minutes and several hours.

Solar Flares

are huge explosions on the Sun. A flare appears as a sudden, intense brightening region on the Sun, typically lasting several minutes to hours. Flares are seen as bright areas on the Sun in optical wavelengths and as bursts of noise in radio wavelengths. The primary energy source of flares is the tearing and reconnection of strong magnetic fields. The electromagnetic emission produced during flares travels at the speed of light, taking about 8 minutes—rapidly affecting the dayside of Earth.

Coronal Mass Ejections

are explosive outbursts of plasma from the Sun's outer atmosphere, the Corona. The blast of a CME typically carries roughly a billion tons of material outward from the Sun at speeds as fast as hundreds of kilometers per second. A CME contains particle radiation (mostly protons and electrons) and powerful magnetic fields. In contrast to solar flares, CMEs are not particularly bright, may take hours to fully erupt from the Sun, and typically take 1-4 days to travel to Earth.

Below is an example of a CME erupting from the Sun. Source: NASA.

SPACE WEATHER AND THE SOLAR CYCLE

The number of sunspots on the surface of the Sun increases and decreases in solar cycles of approximately 11 years. Solar Minimum refers to the several years when the number of sunspots is lowest; Solar Maximum occurs in the years when sunspots are most numerous. The Sun is usually very active when sunspot counts are high, however, severe storms can occur anytime during the solar cycle. Sunspots show where the Sun's magnetic field energy is building up and where it could release to cause solar flares and CMEs. The Sun gives off more radiation than usual during solar maximum. This extra energy creates changes in the Earth's upper atmosphere.

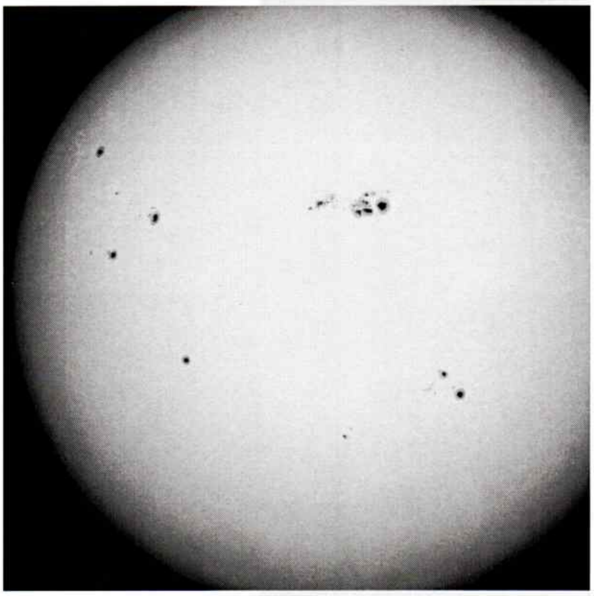
Sunspots

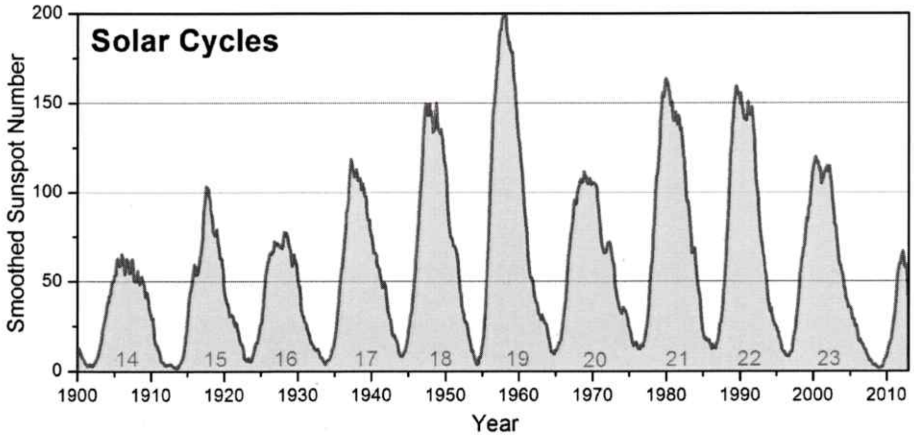
are dark, cooler areas on the solar surface that contain strong, constantly shifting magnetic fields. A moderate-sized sunspot is many times larger than the size of the Earth.

Sunspots form over periods lasting from days to weeks, and can persist for weeks and even months before erupting or dissipating.

Sunspots occur when strong magnetic fields emerge through the solar surface and allow the area to cool slightly, from a background value of 6000°C down to about 4200°C. This cooler area appears as a dark spot on the Sun. As the Sun rotates, sunspots on its surface appear to move from left to right. It takes the Sun 27 days to make one complete rotation.

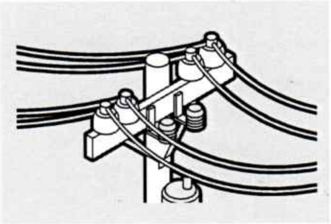
The image below shows a large sunspot cluster at the center of the Sun, extending more than 100,000 km from end to end. Each of the dark cores is larger than Earth. Source: NASA/SDO.





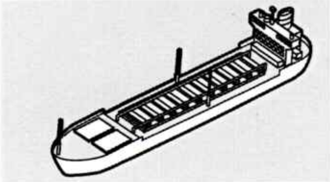
Shown is the approximately 11 year quasi-periodic variation in the sunspot number. The polarity pattern of the magnetic field reverses with each cycle. An increase of solar activity, such as solar flares and CMEs, occurs frequently during the maximum sunspot period.

WHAT ARE THE IMPACTS OF SPACE WEATHER?



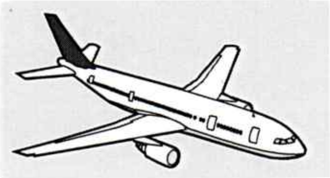
Electric Power

Large currents in the ionosphere can induce currents in power lines. Surges from these induced currents can cause massive network failures and permanent damage to electric grid components.



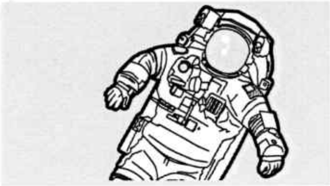
Navigation Systems

Disturbances in the ionosphere can cause degradation in GPS range measurements and in severe circumstances, loss of lock by the receiver on the GPS signal.



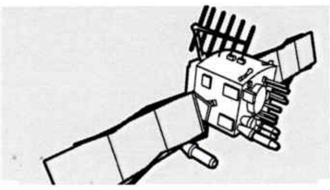
Aviation

Space weather storms can cause lost or degraded communications, radiation hazards to crew and passengers, unreliable navigational information, and problems with flight-critical electronic systems.



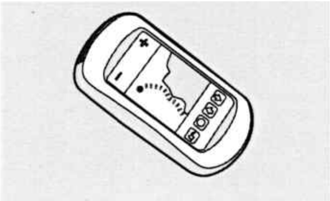
Human Space Exploration

Energetic particles present a health hazard to astronauts on space missions as well as threats to electronic systems. During space missions, astronauts outside spacecraft are less protected and more exposed to space radiation.



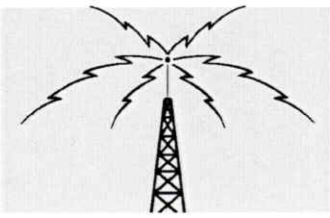
Satellite Operations

Highly energetic ions penetrate electronic components, causing bit-flips in a chain of electronic signals that can result in improper commands within the spacecraft or incorrect data from an instrument. Less energetic particles contribute to a variety of spacecraft surface charging problems, especially during periods of high geomagnetic activity.



Surveying

Magnetic field changes associated with geomagnetic storms directly affect operations that use the Earth's magnetic field for guidance, such as magnetic surveys, directional drilling, or the use of magnetic compasses. Ionospheric disturbances cause errors in location obtained from GPS signals.



Communications

Communications at all frequencies may be affected by space weather. High frequency (HF) radio communications are more routinely affected because this frequency band depends on reflection by the ionosphere to carry signals great distances.

WHO BENEFITS FROM SPACE WEATHER FORECASTS?

Accurate and timely space weather information is vital in mitigating storm impacts on our technological infrastructure. Geomagnetic storms can cause widespread electrical blackouts, resulting in significant loss of life and a potential economic loss in the billions of dollars. Polar flights rerouted due to space weather cost airlines an average of more than $100,000 per flight. If airborne survey data or marine seismic data are degraded by solar activity, the financial impacts can range from $50,000 to $1,000,000.

Primary Users of Space Weather Data

Electric Power Grid Operators use geomagnetic storm detection and warning products to maximize power grid stability and to mitigate power grid component damage and large-scale blackouts.

Spacecraft Launch Operators use radiation products to avoid electronic problems on navigation systems, preventing launch vehicles from going off course and being destroyed.

Spacecraft Operations and Design staff rely on space weather products to avoid electronic problems. Space weather effects on satellites vary from simple repairs to total mission failure.

Manned Spaceflight activities are altered to avoid or mitigate effects of radiation storms impacting crews and technological systems.

Navigation Systems depend on space weather information to ensure the integrity and safe use of electronic navigational systems, such as GPS.

Aviation Operators use crucial information on space weather impacts—such as communication outages, potentially harmful radiation, and navigation errors—to adjust routes and altitudes.

Communications Operators anticipate and react to space weather activity to mitigate impacts occurring over a wide range of communications frequencies used by emergency management officials, search and rescue systems, and many others.

Surveying and Drilling Operations rely on accurate and timely space weather products for safe and efficient high-resolution land surveying and sea drilling.

A growing number of customers are realizing societal and economic benefits from space weather products and services. Expect this trend to continue as the world becomes increasingly dependent on space-based systems and other technologies vulnerable to hazardous space weather.

Without space weather forecasts industry can lose:

$100 Billion
Loss in space assets from a worst-case space weather storm

$1 Million
Loss to surveying and drilling companies to halt operations due to space weather

$100,000
Cost to divert a polar flight due to space weather

HOW IS SPACE WEATHER PREDICTED?

A space weather forecast begins with a thorough analysis of the Sun. Forecasters use many different types of solar images to analyze active solar regions, localized areas that typically contain enhanced magnetic fields and sunspots. Sunspot groups can be many times the size of Earth and contain complex magnetic structures. Forecasters analyze the size of active regions, assess their magnetic complexity, and evaluate growth and decay. Following this analysis, forecasters will predict the probability of a solar flare.

NOAA Space Weather Prediction Center Forecast office. Source: NOAA.

Forecasters use a number of computer models to determine the likely effects of solar events on Earth's atmosphere and magnetosphere. These models help forecasters estimate when the effects will begin, how long they will last, and how severe the event will be. Space weather forecasters also analyze the 27-day recurrent pattern of solar activity. Based on a thorough analysis of current conditions, compared to past conditions, forecasters use numerical models to predict space weather on times scales ranging from hours to weeks.

NOAA's Space Weather Prediction Center (SWPC), located in Boulder, Colorado, operates 24 hours a day and 7 days a week. SWPC continuously monitors conditions on the Sun using data received from spacecraft and ground-based observatories around the globe. SWPC leverages space weather observations, as well as research and development supported by the National Science Foundation and National Aeronautics and Space Administration (NASA), the Department of Defense and the U.S. Geological Survey.

SWPC works closely with the Air Force Weather Agency to ensure forecast coordination and product compatibility between the civil and military sectors. In addition to being the official source of U.S. civilian space weather alerts and warnings, SWPC serves as the World Warning Agency for the 14 Regional Warning Centers of the International Space Environment Services (ISES): Australia, Belgium, Brazil, Canada, China, Czech Republic, India, Japan, Korea, Poland, Russia, South Africa, and Sweden.

SWPC forecasters communicate current and future space weather conditions and the possible effects using a variety of products. Some of the products reference the NOAA Space Weather Scales. These scales are similar to those describing hurricanes (e.g., Category 4), tornadoes (e.g., EF-5), and earthquakes (e.g., 7 on the Richter Scale). Space weather scales describe radio blackouts (R1-5), solar radiation storms (S1-5), and geomagnetic storms (G1-5). The scales list possible impacts for each level (see Pages 9-11). The scales also indicate how often such events happen and give a measure of the intensity of the physical causes (i.e., x-ray flares, proton fluxes, or magnetic disturbances).

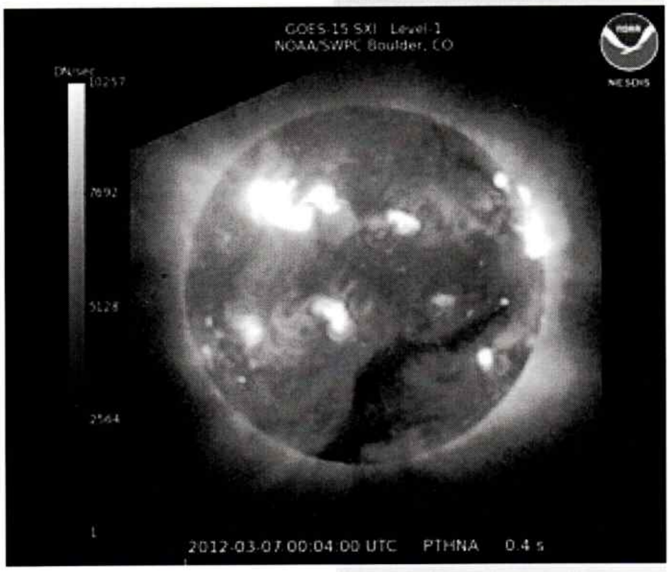
SPACE WEATHER STORMS

Radio Blackouts

Radio Blackouts are caused by bursts of X-ray and Extreme Ultra Violet radiation emitted from solar flares. Radio blackouts primarily affect High Frequency (HF) (3-30 MHz) communication, although fading and diminished reception may spill over to Very High Frequency (VHF) (30-300 MHz) and higher frequencies. These storms are a consequence of enhanced electron densities caused by solar flare emissions. The emissions ionize the sunlit side of Earth, which increases the amount of energy lost as radio waves pass through this region.

Radio blackouts are among the most common space weather events to affect Earth. Minor events occur, on average, 2000 times each solar cycle. Blackouts are by far the fastest to impact our planet. The X-rays creating radio blackouts arrive at the speed of light–8 minutes from Sun to Earth, making advance warnings difficult. When flares occur, however, SWPC measures their intensity and forecasts their duration. Usually the radio blackouts last for several minutes, but they can last for hours.

The impacts of Radio Blackouts are felt by industries relying on HF radio communication and low frequency signals, primarily the aviation and marine industries.



Above is an example of a solar flare. Flares can result in lost or degraded communications and navigation position errors. Source: NOAA/GOES-15.

Solar Radiation Storms

Solar radiation storms occur when large quantities of charged particles, protons and electrons, are accelerated by processes at or near the Sun. When these processes occur, the near-Earth satellite environment is bathed with high energy particles. Earth's magnetic field and atmosphere offer some protection from this radiation, but the amount of protection is a function of altitude, latitude, and magnetic field strength. The polar regions are most affected by energetic particles because the magnetic field lines at the poles extend vertically downwards, allowing the particles to spiral down the field lines and penetrate into the atmosphere, increasing ionization.

Energetic protons reach Earth a half hour to several hours after a solar eruption. Solar radiation storms can last from a few hours to days, depending on the magnitude of the eruption. Solar radiation storms can occur at any time during the solar cycle but tend to be most common around solar maximum.

Solar radiation storm impacts include loss of HF radio communications through the polar regions, navigation position errors, elevated radiation exposure to astronauts, and to passengers and crew in aircraft at high altitudes and latitudes, and damage to satellite systems.

Geomagnetic Storms

Geomagnetic storms, strong disturbances to Earth's magnetic field, pose problems for many activities, technological systems, and critical infrastructure. The Earth's magnetic field changes in the course of a storm as the near-Earth system attempts to adjust to the jolt of energy from the Sun carried in the solar wind. CMEs and their effects can disturb the geomagnetic field for days at a time.

The most visible attribute of a geomagnetic storm is the aurora, which becomes brighter and moves closer to the equator. This heightened aurora signals the vigorous electrodynamic processes at play as they respond to the burst of energy.

Geomagnetic storms usually last a few hours to days. The strongest storms may persist for up to a week. A string of CMEs may cause prolonged disturbed periods related to the additional energy being pumped into Earth's magnetic field. The frequency of geomagnetic storms, in general, depends on where we are in the solar cycle–with most storms occurring near solar maximum; however, these storms are also common in the declining phase due to high-speed solar wind streams.

Geomagnetic storms induce currents that can have significant impact on electrical transmission equipment. Electric power companies have procedures in place to mitigate the impact of geomagnetic storms.

Example of an Aurora Borealis or Northern Lights. Source: U.S. Air Force.

NOAA Space Weather Scale: **Geomagnetic Storms**

Category	**Effect**	**Physical Measure**	**Average Frequency (1 cycle= 11 years)**
Scale/ Descriptor	**Duration of Event Influences Severity of Effects**	**Kp values* determined every 3 hours**	**Events when Kp level met; (# of storm days)**
G5 Extreme	**Power systems:** widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	**Kp=9**	**4 per cycle** (4 days per cycle)
G4 Severe	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	**Kp=8**	**100 per cycle** (60 days per cycle)
G3 Strong	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	**Kp=7**	**200 per cycle** (130 days per cycle)
G2 Moderate	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	**Kp=6**	**600 per cycle** (360 days per cycle)
G1 Minor	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	**Kp=5**	**1700 per cycle** (900 days per cycle)

*Based on this measure but other physical measures are also considered.

**For specific locations around the globe, use geomagnetic latitude to determine likely sightings

NOAA Space Weather Scale: **Solar Radiation Storms**

Category	**Effect**	**Physical Measure**	**Average Frequency (1 cycle=11 years)**
Scale/ Descriptor	**Duration of Event Influences Severity of Effects**	**Flux level of ≥ 10 MeV particles (ions)***	**Number of events when flux level was met (# of storm days**)**
S5 Extreme	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S4 Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S3 Strong	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S2 Moderate	**Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** infrequent single-event upsets possible. **Other systems:** effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1 Minor	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles$\cdot s^{-1} \cdot ster^{-1} \cdot cm^{-2}$. Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

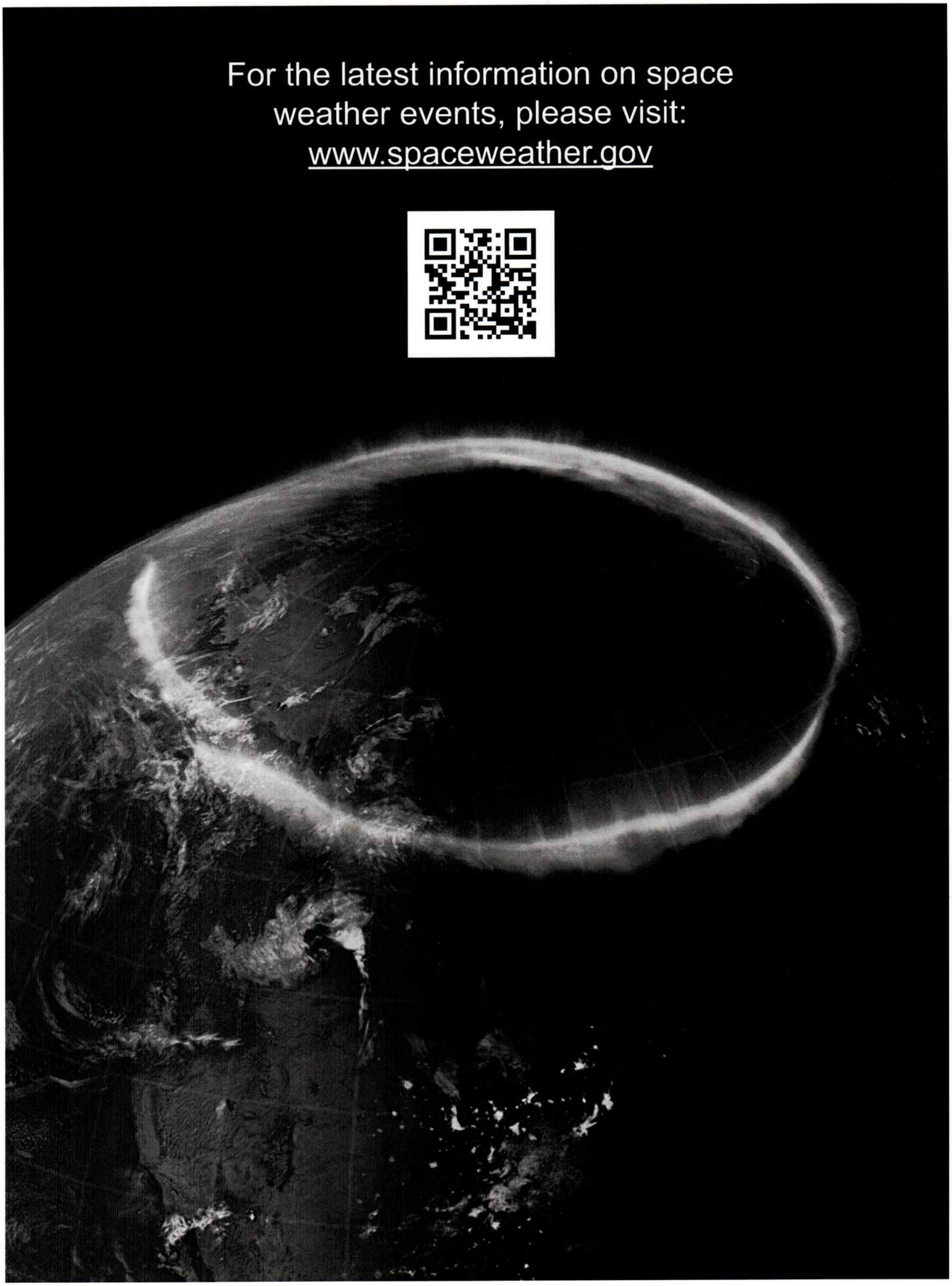
NOAA Space Weather Scale: **Radio Blackouts**

Category	**Effect**	**Physical Measure**	**Average Frequency (1 cycle=11 years)**
Scale/ Descriptor	**Duration of Event Influences Severity of Effects**	**GOES X-ray peak brightness by class and by flux***	**Number of events when Flux level was met; (# of storm days)**
R5 Extreme	**HF Radio:** Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Less than 1 per cycle
R4 Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X1 (10^{-3})	8 per cycle (8 days per cycle)
R3 Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R2 Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M1 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R1 Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

NOAA Space Weather Scales are online at www.spaceweather.gov



For the latest information on space weather events, please visit:
www.spaceweather.gov