

Figure 15.22 Solar Cycle. This dramatic sequence of images taken from the SOHO satellite over a period of 11 years shows how active regions change during the solar cycle. The images were taken in the ultraviolet region of the spectrum and show that active regions on the Sun increase and decrease during the cycle. Sunspots are located in the cooler photosphere, beneath the hot gases shown in this image, and vary in phase with the emission from these hot gases—more sunspots and more emission from hot gases occur together. (credit: modification of work by ESA/NASA/SOHO)

For example, flares are more likely to occur near sunspot maximum, and the corona is much more conspicuous at that time (see [Figure 15.22](#)). A place on the Sun where a number of these phenomena are seen is called an **active region** ([Figure 15.23](#)). As you might deduce from our earlier discussion, active regions are always associated with strong magnetic fields.

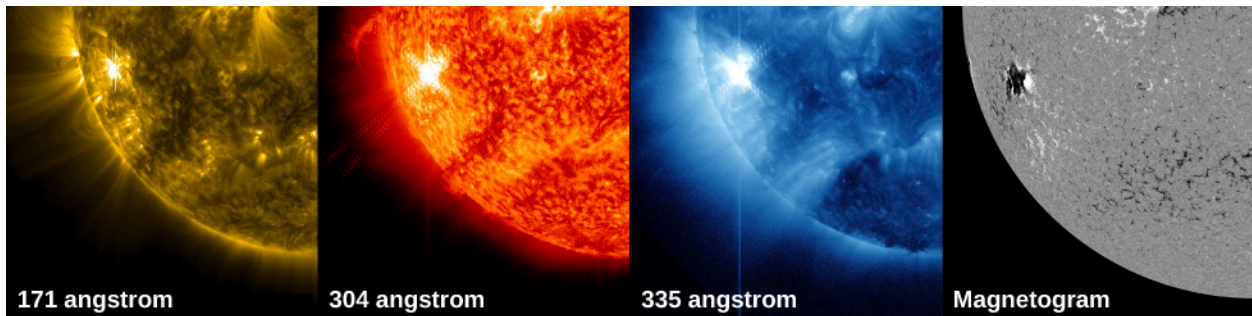


Figure 15.23 Solar Active Region Observed at Different Heights in the Sun's Atmosphere. These four images of a solar flare on October 22, 2012, show from the left: light from the Sun at a wavelength of 171 angstroms, which shows the structure of loops of solar material in the corona; ultraviolet at 304 angstroms, which shows light from the region of the Sun's atmosphere where flares originate; light at 335 angstroms, which highlights radiation from active regions in the corona; a magnetogram, which shows magnetically active regions on the Sun. Note how these different types of activity all occur above a sunspot region with a strong magnetic field. (credit: modification of work by NASA/SDO/Goddard)

15.4 Space Weather

Learning Objectives

By the end of this section, you will be able to:

- Explain what space weather is and how it affects Earth

In the previous sections, we have seen that some of the particles coming off the Sun—either steadily as in the solar wind or in great bursts like CMEs—will reach Earth and its *magnetosphere* (the zone of magnetic

influence that surrounds our planet). As if scientists did not have enough trouble trying to predict weather on Earth, this means that they are now facing the challenge of predicting the effects of solar storms on Earth. This field of research is called *space weather*; when that weather turns stormy, our technology turns out to be at risk.

With thousands of satellites in orbit, astronauts taking up long-term residence in the International Space Station, millions of people using cell phones, GPS, and wireless communication, and nearly everyone relying on the availability of dependable electrical power, governments are now making major investments in trying to learn how to predict when solar storms will occur and how strongly they will affect Earth.

Some History

What we now study as space weather was first recognized (though not yet understood) in 1859, in what is now known as the Carrington Event. In early September of that year, two amateur astronomers, including Richard Carrington in England, independently observed a solar flare. This was followed a day or two later by a significant solar storm reaching the region of Earth's magnetic field, which was soon overloaded with charged particles (see [Earth as a Planet](#)).

As a result, aurora activity was intense and the northern lights were visible well beyond their normal locations near the poles—as far south as Hawaii and the Caribbean. The glowing lights in the sky were so intense that some people reported getting up in the middle of the night, thinking it must be daylight.

The 1859 solar storm happened at a time when a new technology was beginning to tie people in the United States and some other countries together: the telegraph system. This was a machine and network for sending messages in code through overhead electrical wires (a bit like a very early version of the internet). The charged particles that overwhelmed Earth's magnetic field descended toward our planet's surface and affected the wires of the telegraph system. Sparks were seen coming out of exposed wires and out of the telegraph machines in the system's offices.

The observation of the bright flare that preceded these effects on Earth led to scientific speculation that a connection existed between solar activity and impacts on Earth—this was the beginning of our understanding of what today we call space weather.

LINK TO LEARNING



Watch NASA scientists [answer some questions \(https://openstax.org/l/30SpcWeath\)](https://openstax.org/l/30SpcWeath) about space weather, and [discuss \(https://openstax.org/l/30SpcWeath2\)](https://openstax.org/l/30SpcWeath2) some effects it can have in space and on Earth.

Sources of Space Weather

Three solar phenomena—coronal holes, solar flares, and CMEs—account for most of the space weather we experience. Coronal holes allow the solar wind to flow freely away from the Sun, unhindered by solar magnetic fields. When the solar wind reaches Earth, as we saw, it causes Earth's magnetosphere to contract and then expand after the solar wind passes by. These changes can cause (usually mild) electromagnetic disturbances on Earth.

More serious are solar flares, which shower the upper atmosphere of Earth with X-rays, energetic particles, and intense ultraviolet radiation. The X-rays and ultraviolet radiation can ionize atoms in Earth's upper atmosphere, and the freed electrons can build up a charge on the surface of a spacecraft. When this static charge discharges, it can damage the electronics in the spacecraft—just as you can receive a shock when you walk across a carpet in your stocking feet in a dry climate and then touch a light switch or some other metal object.

Most disruptive are coronal mass ejections. A CME is an erupting bubble of tens of millions of tons of gas blown away from the Sun into space. When this bubble reaches Earth a few days after leaving the Sun, it heats the ionosphere, which expands and reaches farther into space. As a consequence, friction between the atmosphere and spacecraft increases, dragging satellites to lower altitudes.

At the time of a particularly strong flare and CME in March 1989, the system responsible for tracking some 19,000 objects orbiting Earth temporarily lost track of 11,000 of them because their orbits were changed by the expansion of Earth's atmosphere. During solar maximum, a number of satellites are brought to such a low altitude that they are destroyed by friction with the atmosphere. Both the Hubble Space Telescope and the International Space Station ([Figure 15.24](#)) require boosts to higher altitude so that they can remain in orbit.

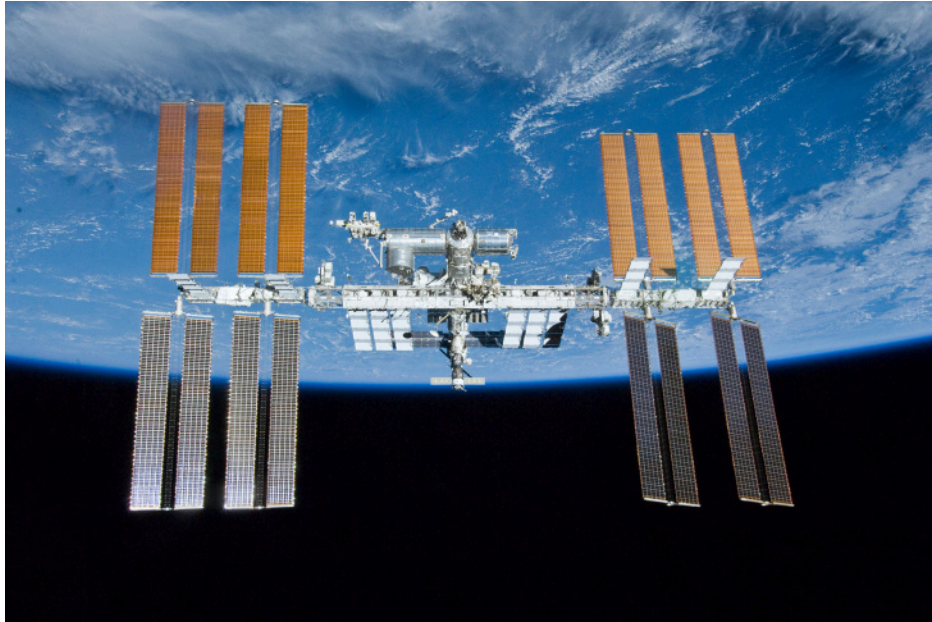


Figure 15.24 International Space Station. The International Space Station is seen above Earth, as photographed in 2010 by the departing crew of the Space Shuttle Atlantis. (credit: NASA)

Solar Storm Damage on Earth

When a CME reaches Earth, it distorts Earth's magnetic field. Since a changing magnetic field induces electrical current, the CME accelerates electrons, sometimes to very high speeds. These "killer electrons" can penetrate deep into satellites, sometimes destroying their electronics and permanently disabling operation. This has happened with some communications satellites.

Disturbances in Earth's magnetic field can cause disruptions in communications, especially cell phone and wireless systems. In fact, disruptions can be expected to occur several times a year during solar maximum. Changes in Earth's magnetic field due to CMEs can also cause surges in power lines large enough to burn out transformers and cause major power outages. For example, in 1989, parts of Montreal and Quebec Province in Canada were without power for up to 9 hours as a result of a major solar storm. Electrical outages due to CMEs are more likely to occur in North America than in Europe because North America is closer to Earth's magnetic pole, where the currents induced by CMEs are strongest.

Besides changing the orbits of satellites, CMEs can also distort the signals sent by them. These effects can be large enough to reduce the accuracy of GPS-derived positions so that they cannot meet the limits required for airplane systems, which must know their positions to within 160 feet. Such disruptions caused by CMEs have occasionally forced the Federal Aviation Administration to restrict flights for minutes or, in a few cases, even days.

Solar storms also expose astronauts, passengers in high-flying airplanes, and even people on the surface of

Earth to increased amounts of radiation. Astronauts, for example, are limited in the total amount of radiation to which they can be exposed during their careers. A single ill-timed solar outburst could end an astronaut's career. This problem becomes increasingly serious as astronauts spend more time in space. For example, the typical *daily* dose of radiation aboard the Russian Mir space station was equivalent to about eight chest X-rays. One of the major challenges in planning the human exploration of Mars is devising a way to protect astronauts from high-energy solar radiation.

Advance warning of solar storms would help us minimize their disruptive effects. Power networks could be run at less than their full capacity so that they could absorb the effects of power surges. Communications networks could be prepared for malfunctions and have backup plans in place. Spacewalks could be timed to avoid major solar outbursts. Scientists are now trying to find ways to predict where and when flares and CMEs will occur, and whether they will be big, fast events or small, slow ones with little consequence for Earth.

The strategy is to relate changes in the appearance of small, active regions and changes in local magnetic fields on the Sun to subsequent eruptions. However, right now, our predictive capability is still poor, and so the only real warning we have is from actually seeing CMEs and flares occur. Since a CME travels outward at about 500 kilometers per second, an observation of an eruption provides several days warning at the distance of Earth. However, the severity of the impact on Earth depends on how the magnetic field associated with the CME is oriented relative to Earth's magnetic field. The orientation can be measured only when the CME flows past a satellite we have put up for this purpose. However, it is located only about an hour upstream from Earth.

Space weather predictions are now available online to scientists and the public. Outlooks are given a week ahead, bulletins are issued when there is an event that is likely to be of interest to the public, and warnings and alerts are posted when an event is imminent or already under way (Figure 15.25).



Figure 15.25 NOAA Space Weather Prediction Operations Center. Bill Murtagh, a space weather forecaster, leads a workshop on preparedness for events like geomagnetic storms. (credit: modification of work by FEMA/Jerry DeFelice)

LINK TO LEARNING



To find public information and alerts about space weather, you can turn to the [National Space Weather Prediction Center \(https://openstax.org/l/30NSWPC\)](https://openstax.org/l/30NSWPC) or [SpaceWeather \(https://openstax.org/l/30SpcWeath3\)](https://openstax.org/l/30SpcWeath3) for consolidated information from many sources.

More satellites are being launched that will allow us to determine whether CMEs are headed toward Earth and how big they are. Models are being developed that will then allow scientists to use early information about the CME to predict its likely impact on Earth.

The hope is that soon, solar weather forecasting will have some of the predictive capability that meteorologists have achieved for terrestrial weather at Earth's surface. However, the most difficult events to predict are the largest and most damaging storms—hurricanes on Earth and extreme, rare storm events on the Sun. Thus, it is inevitable that the Sun will continue to surprise us.

EXAMPLE 15.1

The Timing of Solar Events

A basic equation is useful in figuring out when events on the Sun will impact Earth:

$$\text{distance} = \text{velocity} \times \text{time, or } D = v \times t$$

Dividing both sides by v , we get

$$T = D/v$$

Suppose you observe a major solar flare while astronauts are orbiting Earth. If the average speed of solar wind is 400 km/s and the distance to the Sun is 1.496×10^8 km, how long it will before the charged particles ejected from the Sun during the flare reach the space station?

Solution

The time required for solar wind particles to reach Earth is $T = D/v$.

$$\frac{1.496 \times 10^8 \text{ km}}{400 \text{ km/s}} = 3.74 \times 10^5 \text{ s, or } \frac{3.74 \times 10^5 \text{ s}}{60 \text{ s/min} \times 60 \text{ min/h} \times 24 \text{ h/d}} = 4.3 \text{ d}$$

Check Your Learning

How many days would it take for the particles to reach Earth if the solar wind speed increased to 500 km/s?

Answer:

$$\frac{1.496 \times 10^8 \text{ km}}{500 \text{ km/s}} = 2.99 \times 10^5 \text{ s, or } \frac{2.99 \times 10^5 \text{ s}}{60 \text{ s/min} \times 60 \text{ min/h} \times 24 \text{ h/d}} = 3.46 \text{ d}$$

Earth's Climate and the Sunspot Cycle: Is There a Connection?

While the Sun rises faithfully every day at a time that can be calculated precisely, scientists have determined that the Sun's energy output is not truly constant but varies over the centuries by a small amount—probably less than 1%. We've seen that the number of sunspots varies, with the time between sunspot maxima of about 11 years, and that the number of sunspots at maximum is not always the same. Considerable evidence shows that between the years 1645 and 1715, the number of sunspots, even at sunspot maximum, was much lower than it is now. This interval of significantly low sunspot numbers was first noted by Gustav Spörer in 1887 and then by E. W. Maunder in 1890; it is now called the **Maunder Minimum**. The variation in the number of sunspots over the past three centuries is shown in [Figure 15.26](#). Besides the Maunder Minimum in the seventeenth century, sunspot numbers were somewhat lower during the first part of the nineteenth century than they are now; this period is called the Little Maunder Minimum.

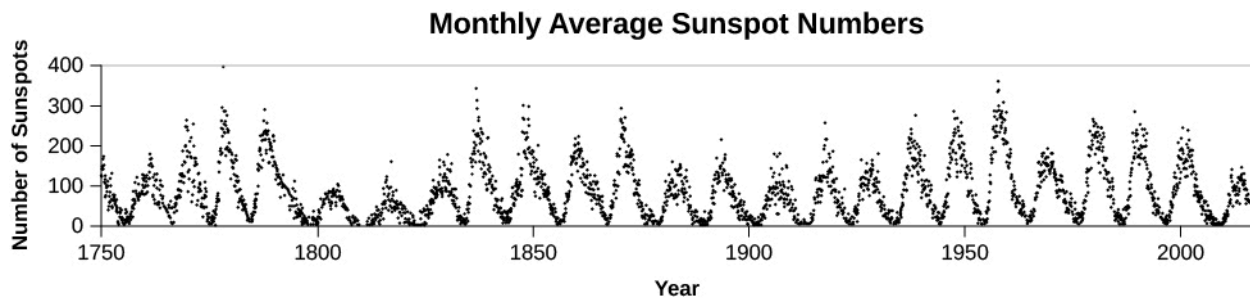


Figure 15.26 Numbers of Sunspots over Time. This diagram shows how the number of sunspots has changed with time since counts of the numbers of spots began to be recorded on a consistent scale. Note the low number of spots during the early years of the nineteenth century, the Little Maunder Minimum. (credit: modification of work by NASA/ARC)

When the number of sunspots is high, the Sun is active in various other ways as well, and, as we will see in several sections below, some of this activity affects Earth directly. For example, there are more auroral displays when the sunspot number is high. Auroras are caused when energetically charged particles from the Sun interact with Earth's magnetosphere, and the Sun is more likely to spew out particles when it is active and the sunspot number is high. Historical accounts also indicate that auroral activity was abnormally low throughout the several decades of the Maunder Minimum.

The Maunder Minimum was a time of exceptionally low temperatures in Europe—so low that this period is described as the Little Ice Age. This coincidence in time caused scientists to try to understand whether small changes in the Sun could affect the climate on Earth. There is clear evidence that it was unusually cold in Europe during part of the seventeenth century. The River Thames in London froze at least 11 times, ice appeared in the oceans off the coasts of southeast England, and low summer temperatures led to short growing seasons and poor harvests. However, whether and how changes on the Sun on this timescale influence Earth's climate is still a matter of debate among scientists.

Other small changes in climate like the Little Ice Age have occurred and have had their impacts on human history. For example, explorers from Norway first colonized Iceland and then reached Greenland by 986. From there, they were able to make repeated visits to the northeastern coasts of North America, including Newfoundland, between about 1000 and 1350. (The ships of the time did not allow the Norse explorers to travel all the way to North America directly, but only from Greenland, which served as a station for further exploration.)

Most of Greenland is covered by ice, and the Greenland station was never self-sufficient; rather, it depended on imports of food and other goods from Norway for its survival. When a little ice age began in the thirteenth century, voyaging became very difficult, and support of the Greenland colony was no longer possible. The last-known contact with it was made by a ship from Iceland blown off course in 1410. When European ships again began to visit Greenland in 1577, the entire colony there had disappeared.

The estimated dates for these patterns of migration follow what we know about solar activity. Solar activity was unusually high between 1100 and 1250, which includes the time when the first European contacts were made with North America. Activity was low from 1280 to 1340 and there was a little ice age, which was about the time regular contact with North America and between Greenland and Europe stopped.

One must be cautious, however, about assuming that low sunspot numbers or variations in the Sun's output of energy *caused* the Little Ice Age. There is no satisfactory model that can explain how a reduction in solar activity might cause cooler temperatures on Earth. An alternative possibility is that the cold weather during the Little Ice Age was related to volcanic activity. Volcanoes can eject aerosols (tiny droplets or particles) into the atmosphere that efficiently reflect sunlight. Observations show, for example, that the Pinatubo eruption in 1991 ejected SO_2 aerosols into the atmosphere, which reduced the amount of sunlight reaching Earth's surface enough to lower global temperatures by 0.4°C .

Satellite data show that the energy output from the Sun during a solar cycle varies by only about 0.1%. We

know of no physical process that would explain how such a small variation could cause global temperature changes. The level of solar activity may, however, have other effects. For example, although the Sun's total energy output varies by only 0.1% during a solar cycle, its extreme ultraviolet radiation is 10 times higher at times of solar maximum than at solar minimum. This large variation can affect the chemistry and temperature structure of the upper atmosphere. One effect might be a reduction in the ozone layer and a cooling of the stratosphere near Earth's poles. This, in turn, could change the circulation patterns of winds aloft and, hence, the tracks of storms. There is some recent evidence that variations in regional rainfall correlate better with solar activity than does the global temperature of Earth. But, as you can see, the relationship between what happens on the Sun and what happens to Earth's climate over the short term is still an area that scientists are investigating and debating.

Whatever the effects of solar activity may be on local rainfall or temperature patterns, we want to emphasize one important idea: Our climate change data and the models developed to account for the data consistently show that solar variability is *not* the cause of the global warming that has occurred during the past 50 years.