

Sun

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The star around which the Earth revolves, and the planet's source of light and heat, hence life. The Sun is a globe of gas, 1.4×10^6 km (8.65×10^5 mi) in diameter with a mass 333,000 times that of the Earth, held together by its own gravity (Table 1). The surface temperature of the Sun is about 6000 K (10,000°F); since solids and liquids do not exist at these temperatures, the Sun is entirely gaseous. Almost all the gas is in atomic form, although a few molecules exist in the coolest surface regions, such as sunspots (**Fig. 1**).

The Sun is a typical member of the spectral class G2 V, dwarf stars of surface temperature 6000 K. The Roman numeral V (“five”) stands for normal stars, known as dwarfs in comparison with the larger stars known as giants or supergiants. Since most stars are cooler and smaller, the Sun is in the upper 5% of stars in its neighborhood.

See also: SPECTRAL TYPE.

Besides its great importance to human life, the Sun is of interest to all astronomers because it is the only star close enough for detailed study of its surface structure. Various surface and atmospheric phenomena such as sunspots and the hot corona may be studied and extrapolated to the trillion or so other stars in our galaxy as well as trillions more in other galaxies. *See also:* STAR.

The light and heat of the Sun, helped by a modest greenhouse effect, make the Earth habitable. The Sun is the ultimate source of nearly all the energy utilized by industrial civilizations in the form of water power, fossil fuels, and wind, not to mention solar energy more directly through solar panels, heating of fluids from mirrors reflecting sunlight, and other burgeoning forms of direct solar energy. Only atomic energy, radioactivity, geothermal heating, and the lunar tides are current nonsolar sources of energy. *See also:* EARTH; ENERGY SOURCES; GREENHOUSE EFFECT; INSOLATION; SOLAR ENERGY.

Solar Structure

The interior of the Sun has long been studied by inference from the observed properties of the entire star, though it is now understood in detail through helioseismology. The Sun's mass, radius, surface temperature, and luminosity are well known. Using the known properties of gases, it is possible to calculate that the structure of the Sun that would produce the parameters observed at the surface. Gravity makes the great mass of the Sun press down on the center, requiring a gas with a central density of near 153 g/cm^3 and a temperature of 1.6×10^7 K (2.8×10^7 °F) to support it. At these huge temperatures and densities, nuclear reactions take place. The

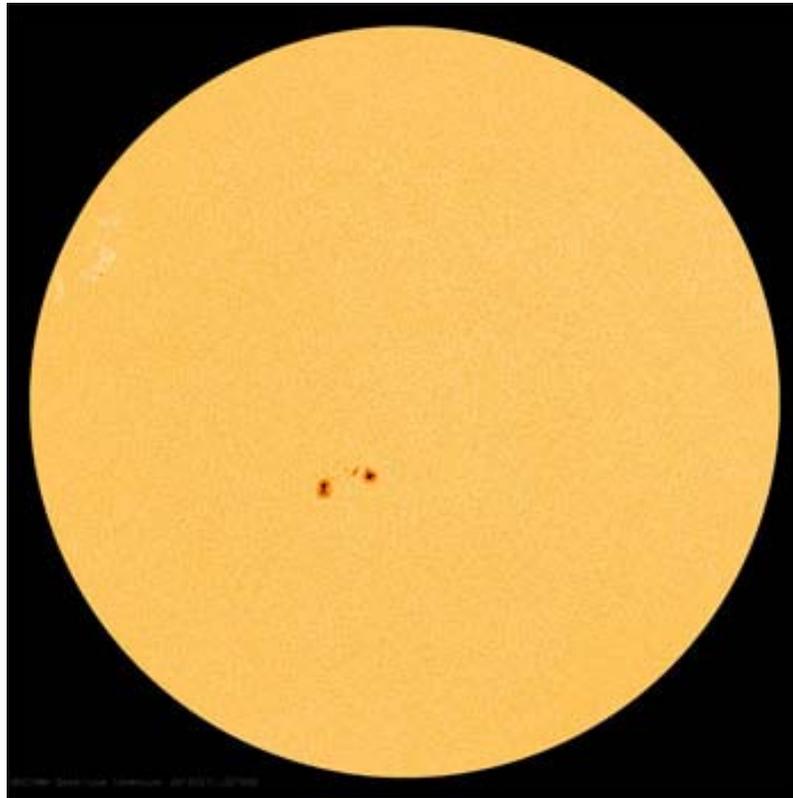


Fig. 1 The Sun, photographed in visible light on February 11, 2012, a time of rising sunspot number. In general, sunspot activity starts at higher latitude and over the 11-year sunspot cycle progresses to lower latitudes in each hemisphere. The magnetic polarities in each hemisphere are opposite, and reverse for the next 11-year cycle, making a full cycle last about 22 years. (*Stanford Lockheed Institute for Space Research/Helioseismic and Magnetic Imager on NASA's Solar Dynamics Observatory*)

radiation produced flows outward until, changing over about a million years from gamma rays to visible light during its random-walk path from the Sun's core, it is radiated into space by the surface (photosphere) at about 5800 K (10,000°F), a temperature equivalent to that radiated by gas at an optical depth of two-thirds. (An optical depth of one represents a diminution of the transmitted intensity by $1/e$.)

Helioseismology

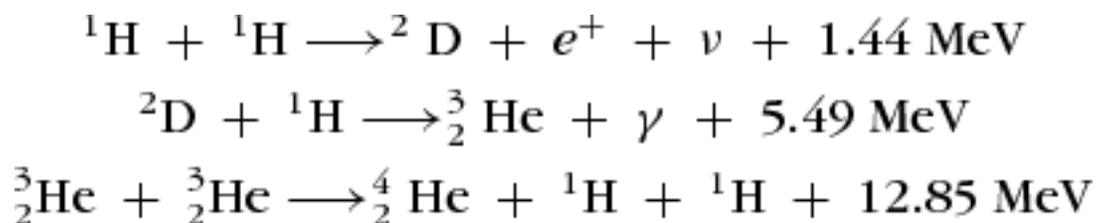
The surface of the Sun is constantly oscillating with a wide range of modes. These motions are the surface manifestation of hundreds of trapped sound waves inside the Sun. The modes are global, coherent over the entire Sun; their lifetimes range from a day to several months. They are characterized by standard spherical harmonics Y_{lm} ; the high-frequency waves stay close to the surface, whereas those of low frequency reach deep into the star. The relation between the frequency and wave number (k ω diagram) specifies the sound speed throughout the Sun and hence the temperature as a function of depth. Comparing this with the pressure yields an estimate of the ratio of hydrogen to helium throughout the star. The National Solar Observatory's Global Oscillation Network

Principal physical characteristics of the Sun	
Characteristic	Value
Mean distance from Earth (the astronomical unit)	$1.4960 \times 10^8 \text{ km} = 9.2956 \times 10^7 \text{ mi}$
Radius	$(6.957 \pm 0.001) \times 10^5 \text{ km} = (4.323 \pm 0.001) \times 10^5 \text{ mi}$
Mass	$(1.9885 \pm 0.0001) \times 10^{33} \text{ g} = (4.3840 \pm 0.0002) \times 10^{30} \text{ lb}$
Mean density	$1.408 \pm 0.001 \text{ g/cm}^3$
Surface gravity	$(2.740 \pm 0.001) \times 10^4 \text{ cm/s}^2 = 899.0 \pm 0.4 \text{ ft/s}^2 = 28 \times \text{terrestrial gravity}$
Total energy output	$(3.8275 \pm 0.0014) \times 10^{33} \text{ erg/s} = (3.8275 \pm 0.0014) \times 10^{26} \text{ W}$
Energy flux at surface	$(6.294 \pm 0.004) \times 10^{10} \text{ erg/(cm}^2\text{)(s)} = (6.294 \pm 0.004) \times 10^7 \text{ W/m}^2$
Effective surface temperature	$5772.0 \pm 0.8 \text{ K} = 9929.9 \pm 1.4^\circ\text{F}$
Stellar magnitude (photovisual)	$-26.73 \pm .03$
Absolute magnitude (photovisual)	$+4.84 \pm .03$
Inclination of axis of rotation to ecliptic	7°
Period of rotation	About 27 days; the Sun does not rotate as a solid body; it exhibits a systematic increase in period from 25 days at the equator to 36 days at the poles

Group (GONG) monitors such solar ringing like a bell from the ground, and instruments on NASA's Solar Dynamics Observatory (SDO) and the European Space Agency's Solar and Heliospheric Observatory (SOHO) monitor the oscillations from space. *See also:* HELIOSEISMOLOGY; SPHERICAL HARMONICS.

Energy production

The energy of the Sun is produced by the conversion of hydrogen into helium by the following process:



For each hydrogen atom converted, one neutrino is produced, giving a flux of 1.3×10^{11} neutrinos $\text{s}^{-1} \text{ cm}^{-2}$ at the Earth. These neutrinos are detected, but only about one-third the expected number. Studies with a variety of materials sensitive to incoming neutrinos over several decades have led to the theoretical conclusion that the shortfall results because neutrinos have a small amount of mass, which causes most of the neutrinos to change

their form in passing through the Sun and in the 8 min that they take to reach Earth. Indeed, neutrinos have recently been found to oscillate among electron, tau, and muon neutrinos, so that three times as many are actually produced as are observed, corresponding to solar models. Many physicists were surprised when the solar models that provided the central solar temperature, needed to predict the neutrino flux, were accurate while their assumption that neutrinos were massless turned out to be incorrect. *See also:* NEUTRINO; SOLAR NEUTRINOS.

The material at the center of the Sun is so dense that a few millimeters are opaque, so the photons created by nuclear reactions are continually absorbed and reemitted and thus make their way to the surface by a random walk. The atoms in the center of the Sun are entirely stripped of their electrons by the high temperatures, and most of the absorption is by continuum processes, such as the scattering of light by electrons. Because there are so many absorption and emission processes along the way, it can take as long as a million years to complete the random walk to the surface.

Convection

In the outer regions of the solar interior, the temperature is low enough for ions and even neutral atoms to form and, as a result, atomic absorption becomes very important. The high opacity makes it very difficult for the radiation to continue outward, so steep temperature gradients are established that result in convective currents. Most of the outer envelope of the Sun, measured from helioseismology to extend 30% of the distance downward from the photosphere, is in such convective equilibrium. These large-scale mass motions are responsible for the complex phenomena observed at the surface. *See also:* CONVECTION (HEAT).

Rotation

Because the Sun is a gaseous plasma, it need not rotate as a solid object such as the Earth. Indeed, observations of sunspots and other features on the Sun's surface show that the equator rotates once in 25 days, while the polar regions rotate in 36 days. The very center must rotate as a solid body. The internal distribution of rotation has been furnished by helioseismology (**Fig. 2**). The internal oscillation modes exhibit a range of frequencies from both approaching and receding hemispheres, and this permits a determination of the rotation rate as a function of depth and latitude. It is thought that solar magnetic fields are based on a dynamo created by the differential rotation. *See also:* SOLAR MAGNETIC FIELD; STELLAR ROTATION.

Radiation

Electromagnetic energy is produced by the Sun at all wavelengths. Important radiation has been measured from long radio waves of 300 m down to x-rays and gamma rays of less than 0.1 nanometer (from rockets). In addition, considerable energy is emitted in the form of high-energy particles (cosmic rays). However, more than 95% of the energy is concentrated in the relatively narrow band between 290 and 2500 nm [2.5 micrometer (μm)] and is accessible to routine observation from ground stations on Earth. The maximum radiation is in the yellow-green

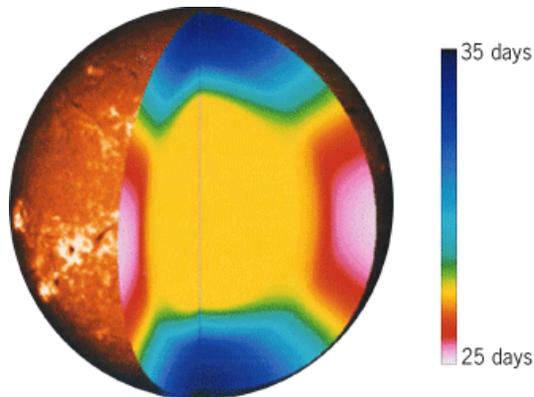


Fig. 2 Map of the differential rotation of the Sun, determined from helioseismology. The poles rotate slowly and the equator much faster, but the center of the Sun, below the convective zone, rotates as a rigid body. (K. G. Libbrecht and M. F. Woodard, *California Institute of Technology*)

region, and the eyes of human beings have naturally evolved to be sensitive to this range of the spectrum. The total radiation and its distribution in the spectrum are parameters of fundamental significance, because they measure the total energy output of the Sun and its effective surface temperature. This quantity was long called the solar constant. Since it is not exactly constant but varies slightly ($\pm 0.1\%$) with the solar cycle, as shown from a series of active cavity radiometers (ACRIM3 is on NASA's ACRIMsat) and the Variability of solar IRradiation and Gravity Oscillations (VIRGO) experiment on SOHO, it is now known as total solar irradiance (TSI). The ultraviolet flux, however, varies by substantial factors depending on the exact wavelength, and this variation affects the Earth's upper atmosphere. Since 2009, it has been monitored by the Extreme ultraviolet Variability Experiment (EVE) on SDO. *See also:* COSMIC RAYS; ELECTROMAGNETIC RADIATION; ROCKET ASTRONOMY; SOLAR CONSTANT; SOLAR RADIATION.

Solar atmosphere

Because the Sun is the only star visible as a two-dimensional surface rather than as a point, the study of its atmosphere and surface phenomena is of special interest.

Although the Sun is gaseous, it can be seen only to the point at which the density is so high that the material is opaque. This layer, the visible surface of the Sun, is termed the photosphere. Light from farther down reaches the Earth by repeated absorption and emission by the atoms; the deepest layers cannot be seen directly. The surface is actually not sharp, but the Sun is so far away that the smallest distance that can be resolved with the best telescope is about 300 km (200 mi). Since the density e-folding height (scale height) is less than 200 km (120 mi), and the human eye can resolve only about 20,000 km (12,000 mi) at the Sun's distance, the edge appears sharp both to the eye and in telescopes.



Fig. 3 Two sections of the Fraunhofer spectrum, showing bright continuum as well as absorption lines (“Fraunhofer lines”), which are dark. The wavelength range covered by each strip is approximately 8.5 nm, essentially a monochromatic part of the spectrum. The three strongest lines shown are produced by magnesium; the others, mostly by iron. (*Sacramento Peak Observatory, operated by the Association of Universities for Research in Astronomy, Inc.*)

Actually, because of the presence of negative hydrogen (H^-) ions, which provide most of the solar opacity in the visible and infrared, the photospheric gas is far more opaque than the terrestrial atmosphere, and the density to which we see is 10,000 times less than at atmospheric density at the Earth’s surface. The H^- ion is formed when an electron attaches to a neutral hydrogen atom. It does not stay bound for long but quickly is detached by absorption of a photon, resulting in so-called bound-free emission. As a result, H^- absorbs radiation voraciously. Mere swerves of the extra electron approaching a hydrogen atom, resulting in free-free emission, also contribute. *See also:* PHOTOSPHERE.

Above the photosphere, the solar atmosphere is transparent, and its density falls off much more slowly because magnetic fields support the ionized particles. The atmosphere can be seen by using a narrow-band filter or a spectrograph to pick out the isolated wavelengths absorbed by the atmospheric gases (the dark lines in **Fig. 3**). In the upper photosphere it is cooler, and the lines are dark. If the light is imaged in the strongest lines, such as those of hydrogen or of ionized calcium, a region higher still is seen, called the chromosphere. The light from this region is dominated by the red hydrogen alpha (level 2 to 3 transition) line, which gives it a rosy color seen at a solar eclipse. The chromosphere is a rapidly fluctuating region of jets (spicules) and waves coming up from the surface. When all the convected energy coming up from below reaches the surface, it is concentrated in the thin material and produces considerable activity. Where the magnetic field is stronger, these waves are absorbed, and raise the temperature to 7000–8000 K (12,000–14,000°F). The scale height of the chromosphere is 1000 km (600 mi) or more, so there no longer is a sharp edge. *See also:* CHROMOSPHERE; ECLIPSE.

When the Moon obscures the Sun at a total solar eclipse, the vast extended atmosphere of the Sun called the corona can be seen. The corona is a million times fainter than the photosphere, so it is visible only when seen against the dark sky of an eclipse or with very special instruments, called coronagraphs, from high altitudes on Earth or from space. Its density is low, but its temperature is high (more than 10^6 K or 1.8×10^6 °F). It is monitored continually with coronagraphs in space, which have revealed the daily ejection of matter as coronal mass ejections (CMEs), which have been shown not to be strictly correlated with solar flares. Images taken continually through extreme-ultraviolet filters at selected wavelengths that correspond to highly ionized species

also show the corona. The hot gas of the corona flows steadily to the Earth and farther in the solar wind. *See also:* CORONAGRAPH; SOLAR CORONA; SOLAR WIND.

Within the solar atmosphere, many transient phenomena occur that may all be grouped under the heading of solar activity. They include sunspots and faculae in the photosphere, flares and plages in the chromosphere, prominences of chromospheric temperature that extend into the corona, and a variety of changing structures in the corona. The existence and behavior of all these phenomena are connected with magnetic fields, and their frequency waxes and wanes in a great 22-year cycle called the sunspot cycle or, more generally, the solar-activity cycle. The sunspots and flares are sources of x-rays, cosmic rays, and radio emission, which often have profound influence on interplanetary space and the upper atmosphere of the Earth.

Solar physics

Scientific study of the Sun is usually called solar physics instead of solar astronomy because of the origin of the field from spectroscopic studies around the beginning of the twentieth century. Understanding of the Sun is often derived from two-dimensional time-lapse observations of the morphology of various phenomena and from physical analysis with the spectrograph and magnetograph. Two-dimensional imaging data give the spatial distribution of different phenomena, and the spectroscopy helps determine the detailed physical parameters of the gas under observation. The images can also give magnetic field and velocity amplitude and distribution. *See also:* ASTRONOMICAL SPECTROSCOPY.

Each of the absorption lines in **Fig. 3** represents some discrete transition in a particular atom that occurs when a photon of light is absorbed and one of the atomic electrons jumps from one level to another, higher level. Of the 92 natural elements, at least 64 are represented in the Fraunhofer spectrum (Table 2). The remaining atoms are undoubtedly present but remain undetected because they are rare or their lines are produced in spectral regions little studied with spectrographs. The relative abundances of the most numerous atoms have been estimated from the line intensities. Many of these abundances have been confirmed by measurement of the relative abundances of different elements in the streams of particles coming from the Sun at the time of solar flares or from analysis of meteorites. We can also conjecture the formation of Sun and planets from the element abundances, and especially the ratios of certain isotopes. The Sun can be described as a globe of chemically (but not spectroscopically) pure hydrogen (90% by number) and helium (almost 10% by number) with traces (0.1%) of the other elements. *See also:* COSMIC ABUNDANCE OF ELEMENTS; COSMOCHEMISTRY; FRAUNHOFER LINES; SOLAR SYSTEM.

Photosphere

The photosphere is the visible surface of the Sun. In the visible wavelengths, its brightness decreases smoothly from the center of the solar disk to the limb. This limb darkening results from the fact that the deepest and hottest sources of radiation are seen at the center of the Sun's disk, and higher and cooler sources at the limb as the line of sight slants through the upper atmosphere, reaching opacity of two-thirds at greater radii than at disk

TABLE 2. Relative numbers of the most abundant atoms in the Sun.*

Element	Number
Hydrogen, H	1,000,000
Helium, He	85,000
Oxygen, O	600
Carbon, C	320
Neon, Ne	90
Nitrogen, N	70
Magnesium, Mg	40
Iron, Fe	33
Silicon, Si	32
Sulfur, S	14
Aluminum, Al	2.8
Argon, Ar	2.5
Calcium, Ca	2.2
Sodium, Na	1.7
Nickel, Ni	1.7

*Based on data from M. Asplund et al., The chemical composition of the Sun, *Annu. Rev. Astron. Astrophys.*, 47:481–522, 2009; and E. Caffau et al., Solar chemical abundances determined with a COSBOLD model atmosphere, *Solar Phys.*, 268:255–269, 2010.

center in visible light. So the limb darkening can be used to measure the temperature gradient as a function of height. Once the range of temperature is known, the variation of limb darkening with wavelength can be used to establish the absorbing properties of the materials at different wavelengths. By combining all the information on limb darkening at different wavelengths, it has been possible to construct reasonably reliable models of the temperature variation through the photosphere. At the same time, the various spectral lines with different excitations from any atom can be matched to this scheme to get the chemical composition.

Granulation

Except for sunspots and accompanying activity, the photosphere is quite uniform over the Sun. The gas pressure dominates the magnetic fields below 1000 gauss (0.1 tesla). The only structure visible in broadband images is the granulation (often called the rice grains), an irregular distribution having the shape of bright corn kernels with dark lanes in between (**Fig. 4**). The grains are Texas-sized, about 1000 km (600 mi) across, and have a life span of about 8 min. The dark lanes between the granules are about 200 km (120 mi) across. The granulation is visible evidence of convective activity below the surface. The bright grains are the tops of hot, rising columns that bring energy up from the interior, while the dark intergranular lanes are the cool downward-moving material.

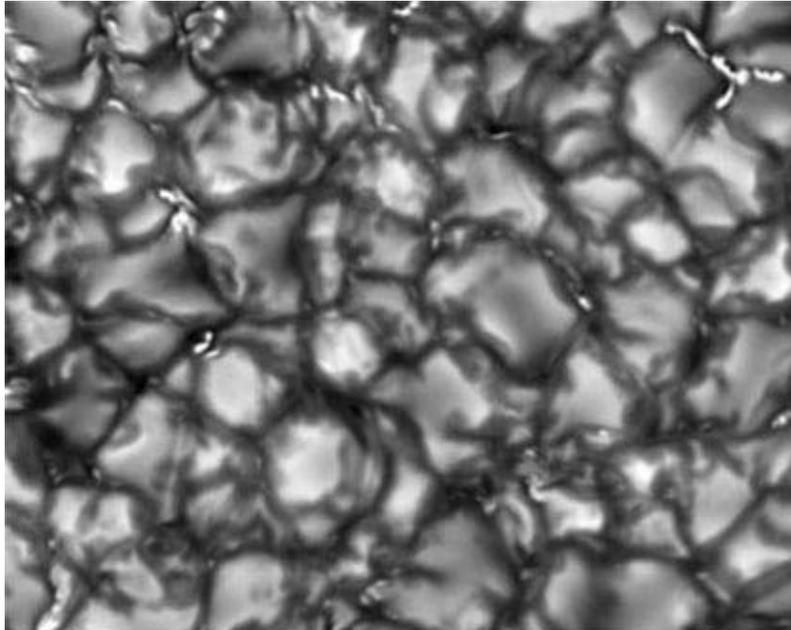


Fig. 4 Photospheric granulation in white light taken with a telescope on a mountain on La Palma, Canary Islands and postprocessed. Individual granules are about 1 arcsec or 800 km (500 mi) on the Sun. (*Royal Swedish Academy of Sciences/Vasco Henriques*)

Sometimes a bright filigree is visible in the dark intergranular lanes. High-resolution spectrograms and Dopplergrams show the corresponding Doppler shifts. The studies of granulation have been aided in recent years by the ability of adaptive optics and postprocessing to compensate for “seeing” variations in the Earth’s atmosphere. No instruments in space have had high resolution to match the best resolution available from the ground. Pixels on the Solar Optical Telescope of the Hinode mission are 0.2 arcsec, while pixels on the Atmospheric Imaging Assembly of *SDO* are 0.5 arcsec, about 400 km. Occasional rockets carry telescopes that can obtain higher resolution for a few minutes. *See also:* ADAPTIVE OPTICS; DOPPLER EFFECT.

Supergranulation

In addition to the granulation, which can be seen in broadband pictures of the Sun’s surface, a larger scale of convection, called the supergranulation, can be seen in Doppler images of the surface, made by subtracting images taken through narrow-band filters on either side (redward or blueward) of spectral lines. The supergranular cells are about 30 granules across, and their life span is about 12 days. There is an outflow to the edges of these cells, concentrating the magnetic fields there. This pattern determines the structure of the upper atmosphere. The magnetic fields near the cell edges transmit energy to the upper atmosphere, so maps in wavelengths that show the chromosphere, especially in the H and K lines of ionized calcium, reveal a pattern of bright regions. This pattern dominates images in ultraviolet and radio wavelengths. In periods of low sunspot activity, it is the major source of ultraviolet emission. Inside the cells little happens, and in fact there are cold

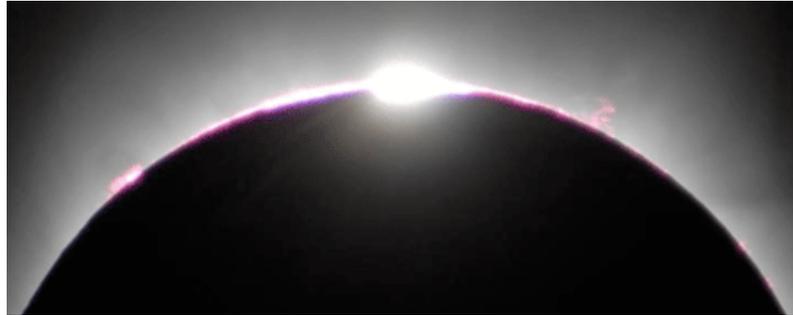


Fig. 5 The diamond-ring effect surrounded along the limb of the Moon by the pinkish chromosphere and the pinkish prominences on either side, viewed at the Easter Island total solar eclipse of 2010. The inner corona is also visible outside the silhouette of the Moon. (Jay M. Pasachoff, Muzhou Lu, and David Amrheim)

regions identified by the appearance of carbon monoxide (CO) in their infrared spectra. *See also:* SUPERGRANULATION.

Chromosphere

The chromosphere was first detected and named by early solar-eclipse observers. They saw it as a beautiful rosy arc that remained visible for a few seconds above the limb of the Moon when the photosphere had been covered and that appeared symmetrically at the end of totality (**Fig. 5**). The chromospheric spectrum is, except for a bare trace of continuum, a pure emission spectrum of bright lines of hydrogen, helium, and singly ionized abundant elements. Because eclipses are rare (total eclipses are visible somewhere on Earth about every 18 months) and the chromosphere can be seen only edge-on at that time, astronomers have developed a special method of photographing the chromosphere in its characteristic lines, particularly $H\alpha$ (**Fig. 6**). In these spectral lines the chromosphere is no longer transparent, and we look at it instead of looking through it to the photosphere.

The study of the morphology of the chromosphere is best carried out by time-lapse motion pictures. If photographs are made every 10 s or so and then are animated on a computer screen at a normal video rate of 30 frames per second, the speedup by a factor of 300 gives a remarkable picture of the dynamic variations in the chromosphere. Such animations of the center and limb of the Sun, first made photographically and now made with charge-coupled devices (CCDs) and other electronic detectors, have provided remarkable pictures of this very complex zone just above the surface of the photosphere. *See also:* ASTRONOMICAL IMAGING; CHARGE-COUPLED DEVICES.

While the magnetic-field energy in the photosphere is considerably less than the energy of the material, the rapid fall-off in density with height results in a situation where the magnetic field dominates the material motions, and the gas is ordered into large-scale patterns. The patterns are not strikingly evident in the low chromosphere (0–1500 km or 0–900 mi), which seems an irregular extension of the underlying photosphere. In fact, the temperature continues to drop above the surface of the photosphere (as evidenced by limb darkening) to an

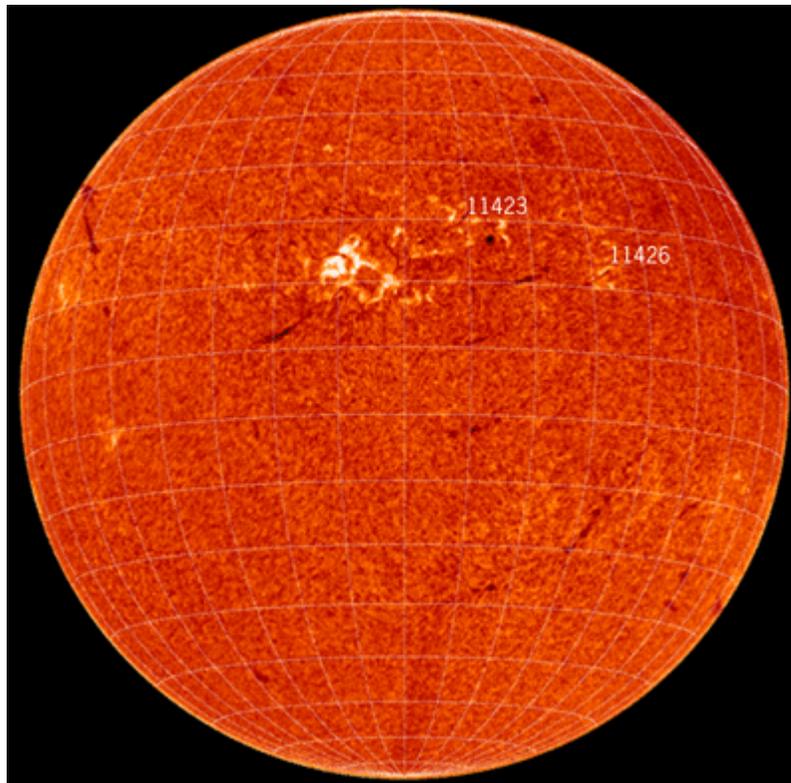


Fig. 6 Image of the Sun in hydrogen-alpha ($H\alpha$) light. As the dark filament at upper left on the disk goes over the limb, it becomes visible as a prominence seen against the sky. The Sun rotates from left to right in this picture. A sunspot is visible in active-region 11423 in this image from March 1, 2012. Every bright area, known as plage (pronounced in French as “plaaaj”), has enhanced magnetic field; every dark streak is a filament (or prominence) separating regions of opposite magnetic polarity. (Kanzelhoehe Observatory, University of Graz, Austria)

apparent minimum of about 4000 K (7000°F) at a height of 1500 km. Even in the low chromosphere, however, the effect of the chromospheric network in the small bright regions of faculae or plages that mark the edge of each network cell is seen. These faculae may be observed in white light near the limb of the Sun. In them the chromosphere shows a very fine structure of bright points, as though we were looking down at each line of force in the magnetic field.

If the edge of the Sun is examined in $H\alpha$, the chromosphere is seen as an irregular band 3000–4000 km (1800–2400 mi) high. If the wavelength is tuned slightly off the line center, the uniform band disappears because it has only a narrow range of wavelength, and a forest of jets called spicules, extending down to the surface, replaces it (Fig. 7). Since the limb is confusing, with many objects in the line of sight, the distribution is better seen on the disk. There the spicules are seen to be clumped and to come only from the small bright faculae that mark the chromospheric network. This is even more marked in the wing of the line (off-band), where the chromosphere is transparent, and only the spicules are seen. The spicules are visible off-band because they are moving rapidly and their spectral lines are Doppler-broadened and usually shifted to longer or to shorter

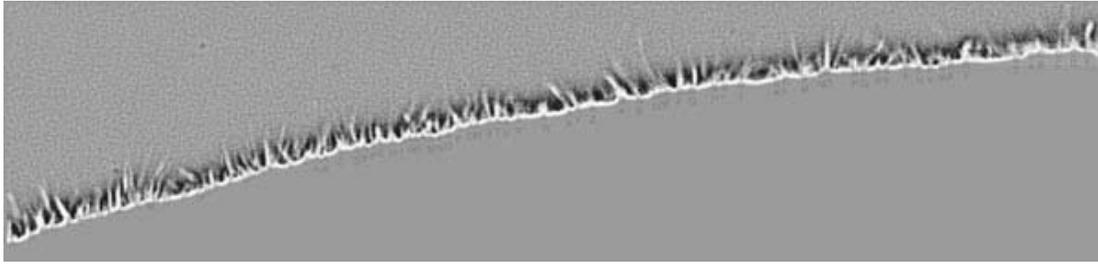


Fig. 7 Photograph of spicules at the edge of the Sun, processed to enhance the fine structure. The higher spicules in this frame are 10,000 km (6000 mi) and last 10–15 min. The smaller spicules last only a few minutes. (Big Bear Solar Observatory, California Institute of Technology)

wavelengths. Magnetic measurements show the faculae to have fairly strong magnetic fields, while velocity measurements show a gentle flow from the center to the edge of the chromospheric network cells and a downflow at the edges. Thus the chromosphere can be regarded as consisting of two components: the general chromosphere (if any), which is evenly distributed (hence independent of magnetic effects) and extends to 7000 km (4200 mi); and the spicule component, which is dynamic, is connected with magnetic fields, and is mostly lower but occasionally extends up to 10,000 km (6000 mi).

Visibility through the Earth's atmosphere and instrumental inadequacies limit the ability to resolve the structure of the spicules. They shoot up to a height of about 6000 km (3600 mi) above the photosphere with a velocity of about 20–30 km/s (12–18 mi/s) and then fade out. They may be very narrow, certainly less than 1000 km (600 mi) across. At the top of their trajectory, some spicules fade out and others drop back into the chromosphere. It is believed that the spicule jets occur as a result of the focusing of mass motions in the low chromosphere by the strong magnetic fields at the edges of the chromospheric network. These magneto-acoustic shock waves form a channel by which energy travels from below into the solar corona to form these classical spicules, now known as type I. Type II spicules, discovered from high-resolution observations in the 2000s with the Solar Optical Telescope on the Hinode spacecraft, are thinner (150–700 km or 90–435 mi), shorter lived (10–100 s), and have higher velocities (50–150 km/s or 30–90 mi/s) than classical spicules. Type II spicules seem to continue upward, in contrast to the reversal of motion detected in type I spicules. They seem to be longer, up to 10 megameters (6000 mi), in coronal holes and shorter, only 2 megameters (1200 mi), in active regions. Identifying spicules seen at the limb with their counterparts seen on the solar disk remains a difficult task.

At the total solar eclipse of 1868, an astronomer found a strong spectral line near the known yellow pair of lines of sodium, the so-called sodium D lines, D_1 and D_2 . When he realized that the new yellow line differed slightly in wavelength, he called it D_3 and said that it was of an unknown element known only on the Sun. He named the element helium, after its source, the Greek Sun-god being Helios; not until 1895 was it isolated on Earth. But helium is a noble gas and normally radiates only at temperatures above 15,000 K (27,000°F). Its presence suggested that the chromosphere had some hot regions. Yet the helium was mainly observed in lower regions of

the chromosphere. The mystery was solved when it was found that a strong source of soft x-rays, which could excite the helium, overlies the chromosphere. This source is the solar corona, in which the temperature rises to over 10^6 K (2×10^6 F). The region in which this rise takes place is called the transition region, from which most of the solar ultraviolet radiation is emitted. Very little was known about it, except that it is very narrow and probably limited to cell boundaries and active regions, but the Atmospheric Imaging Assembly of SDO has filters that can show gas at transition-region temperatures.

Why is the chromosphere extended? It must be due to magnetic support, although the field structures are hard to verify.

Corona

It was long known that a halo of pearly light extends far out from the Sun during a total solar eclipse. Spectral lines of unknown elements were observed beginning with the total solar eclipse of 1869 and labeled coronium because it was thought to exist only in the corona, in parallel to the helium that had been discovered at the previous eclipse. In 1942, by extrapolation along isoelectronic sequences, these were identified as due to highly ionized elements, such as Fe^{13+} , which could exist only at million-degree temperatures (**Figs. 8 and 9**). Why the temperature should run up to such values is still debated, though there are many models and the dominant models involve the solar magnetic field. In general, the vast energy of the photosphere is concentrated in the few atoms of the corona, so the high individual particle velocities are indicated as a high temperature. When the density is so low, emission, which is produced by electron-ion collisions, is weak; once hot, the corona is slow to cool. Though some of the coronal light seen at eclipses is from such emission from highly ionized species, most of the visible coronal radiation is scattered photospheric light. Some, highly polarized, is scattered off coronal electrons, and is known as the K corona (for continuous light, in German, since Doppler broadening all but eliminates the absorption lines); other contributions, especially farther out, are scattered off interplanetary dust, and since the scattered light contains the normal photospheric spectrum, it is known as the F corona (for Fraunhofer).

In observations from satellites above the atmosphere, the situation is different. In the extreme-ultraviolet and x-ray wavelengths, now accessible, only hot gases can emit. Thus, an x-ray picture of the Sun is a picture of the corona. Satellites have thus given continuous images of the corona in many spectral lines (**Figs. 10 and 11**), and special satellite coronagraphs have imaged the corona far from the Sun. Coronagraphs are now aloft on SOHO at a Lagrange point about 1.5×10^6 km (0.9×10^6 mi) toward the Sun from the Earth and on the pair of Solar TERrestrial Relations Observatories (STEREO), which are more than a quarter of the way around the Earth's orbit (STEREO-Ahead and STEREO-Behind), providing views of the Sun's far side. *See also:* X-RAY ASTRONOMY.

As previously noted, the light seen from the corona originates in three distinct processes that distinguish the F (Fraunhofer), K (Kontinuierlich, that is, continuous), and E (emission) components. The F corona is a halo of sunlight scattered by interplanetary dust and is really the inner zodiacal light. With current infrared capabilities, a T (thermal) component is also detectable. *See also:* ZODIACAL LIGHT.

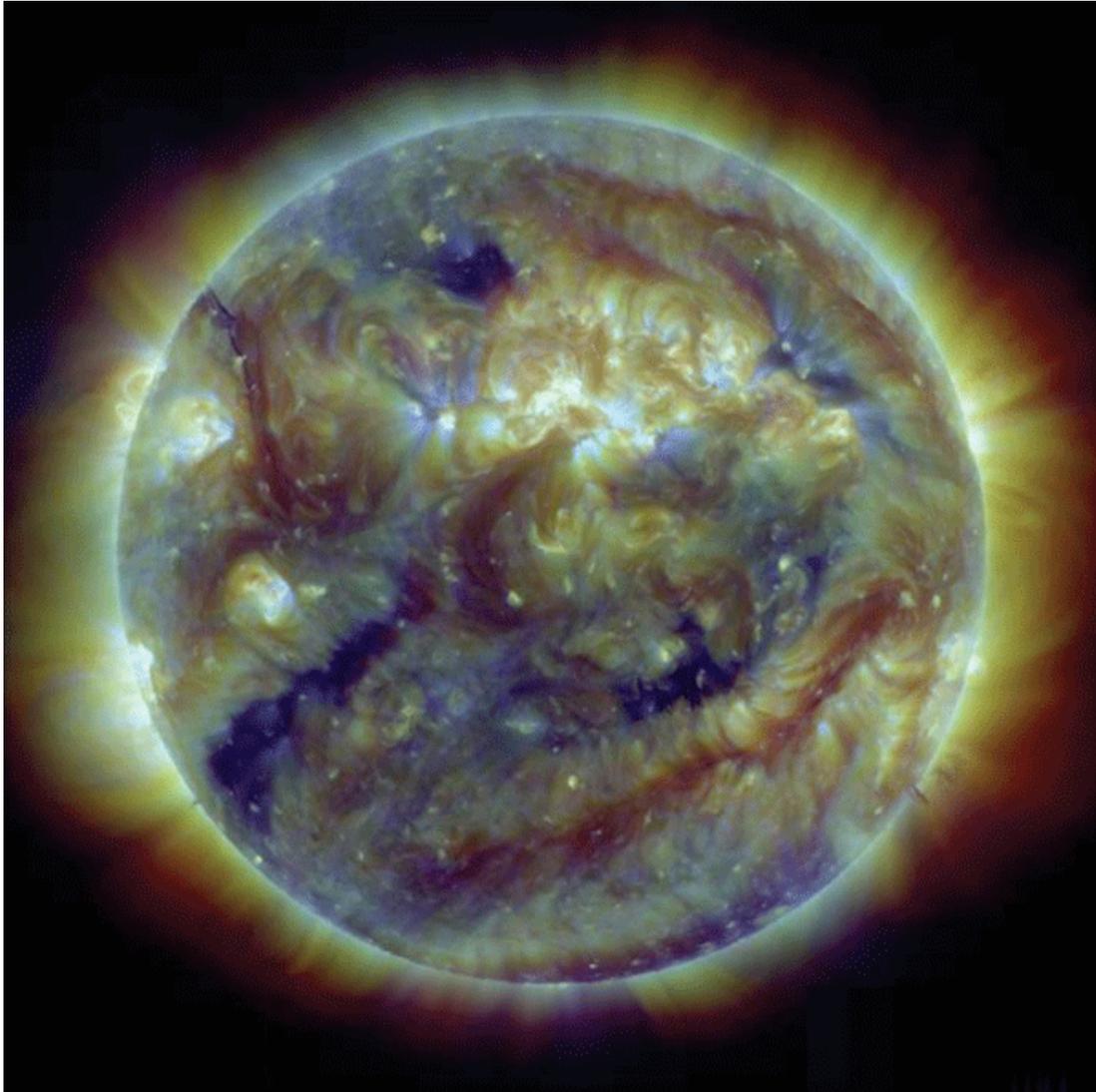


Fig. 8 A false-color composite from three (out of the possible ten) wavelengths imaged with the Atmospheric Imaging Assembly, built by the Smithsonian Astrophysical Observatory for NASA's Solar Dynamics Observatory (SDO), launched in 2010. Blue corresponds to the 17.1 nm spectral line from Fe^{9+} , typical of a temperature of about 630,000 kelvins; green to the 19.3 nm spectral line from Fe^{11+} , typical of a temperature of 1,200,000 kelvins; and red to the 21.1 nm spectral line from Fe^{13+} , typical of a temperature of 2 million kelvins. (NASA's Goddard Space Flight Center/SDO AIA Team)

The K corona is photospheric light scattered by the free electrons in the solar corona. Although this light is not truly emitted by the corona, it is an important tracer of the coronal material, particularly because its intensity is proportional to the electron number and does not fall off so rapidly with height as the emission lines and x-rays, which fall off as density squared. The scattering process introduces polarization, which helps greatly in isolating it. Though the resolution of satellite observations is inferior to that of eclipse observations, they have the advantage of being continuous. They have made possible the viewing of coronal mass ejections (CMEs), bubbles

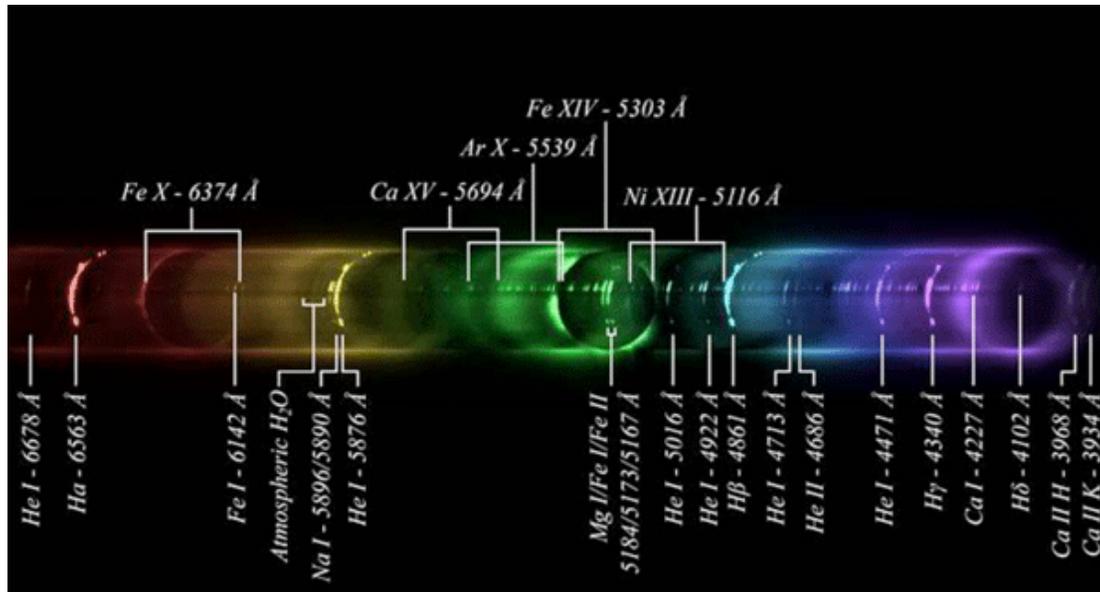


Fig. 9 A flash spectrum from the total solar eclipse of 2010 as viewed from Easter Island, showing the chromospheric spectral lines as arcs, with the full circles representing the coronal lines of Fe X (Fe^{9+} , one fewer ionization stage than the Roman numeral of the ionization state since the neutral state is Fe I, called the coronal red line), Ca XV, Ar X, Fe XIV (called the coronal green line), and Ni XIII. It is a "slitless spectrum," with the narrow arcs or circles of solar radiation acting as their own slits. $1 \text{ \AA} = 0.1 \text{ nm}$. (Aris Voulgaris, John Seiradakis, Jay Pasachoff, Pavlos Gaintatzis, and Thanasis Economou)

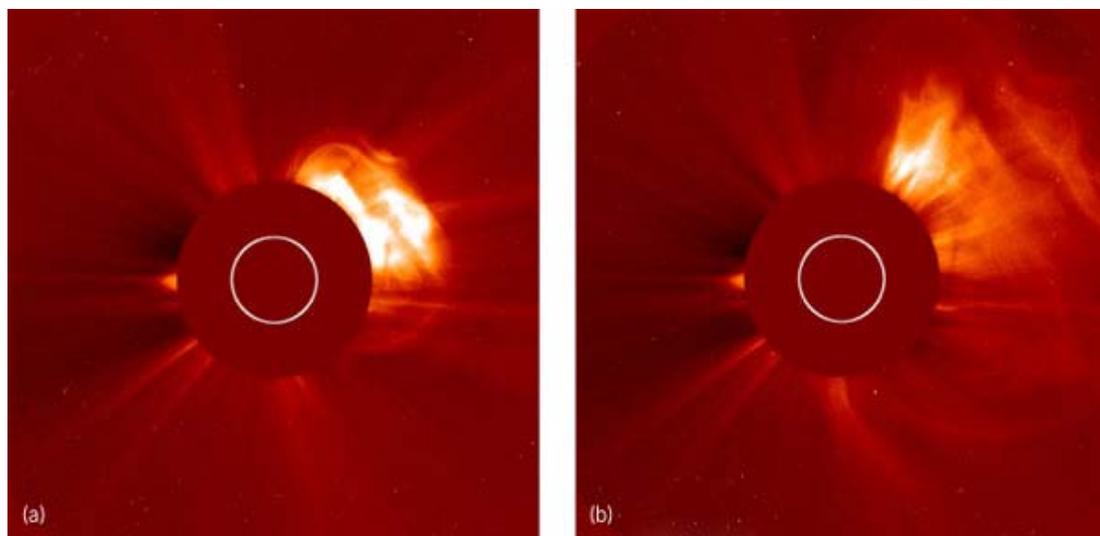


Fig. 10 Large coronal mass ejection on March 21, 2011, as recorded by second coronagraph of three that comprise the Large-Angle Spectroscopic Coronagraph (LASCO C2) on the Solar and Heliospheric Observatory (SOHO). Frames (a) and (b) were separated by 36 min. The occulting disk is about twice the solar diameter. (NASA; European Space Agency, the LASCO team)

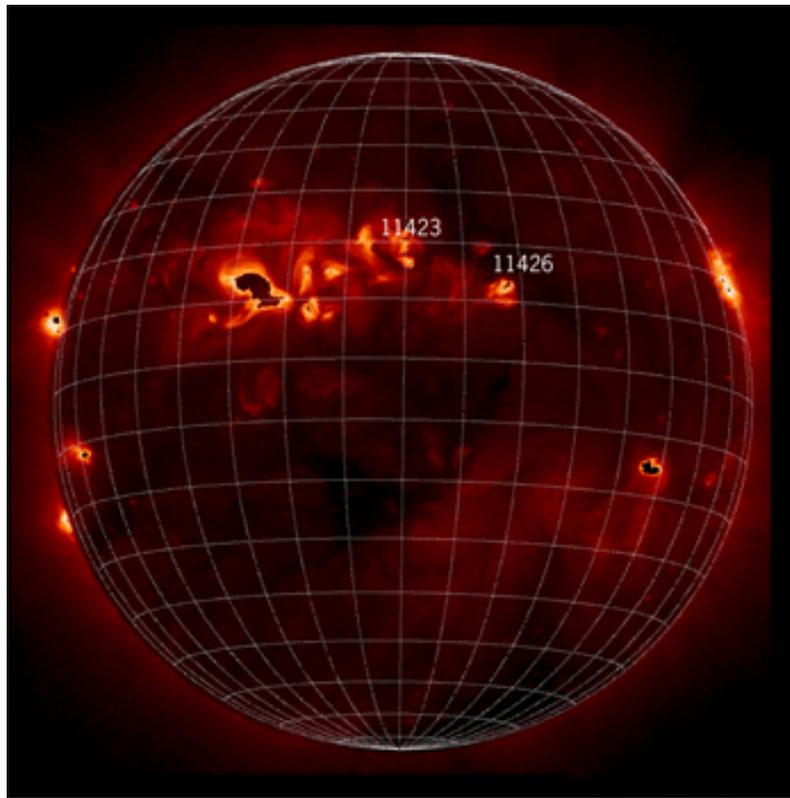


Fig. 11 The Sun in x-rays, as imaged on February 29, 2012 from the X-ray Telescope (XRT), built by the Smithsonian Astrophysical Observatory and operated on the Japanese Hinode spacecraft. (Lockheed Martin Solar and Astrophysics Laboratory and Smithsonian Astrophysical Observatory/NASA/JAXA)

of coronal material flying out to the Earth. Thousands of comets have also been discovered as they go too close to the Sun to be otherwise detected. *See also:* COMET.

The E, or emission-line, corona is the true conversion of the internal energy of the corona into photons. As the images show, it is concentrated in active regions, where the ions are trapped by the magnetic fields and heated by magnetic processes. In these regions, lines of Fe^{15+} and ions of corresponding elements are strong. But away from the active regions, there always are million-degree lines of Fe^{9+} present. In solar flares, the corona is heated up to 3×10^7 K (5.4×10^7 °F), and even lines of iron so hot that only one electron is left are recorded.

Solar wind

One surprise of the age of rockets and satellites has been the discovery of the solar wind. This continual outflow of matter from the Sun was predicted on the basis that the high temperature in the corona must lead to a rapid outflow at great distances from the Sun. A variety of spacecraft has detected a continual flow of plasma from the Sun with velocities ranging 300–500 km/s (180–300 mi/s) and density about 1 atom/cm³ near the Earth. The flow occurs because the conductivity in the corona is so high that the temperature falls off more slowly than

solar gravity, so that at roughly five solar radii the gas is no longer bound. The ions flow along a spiral path dictated by magnetic fields from the Sun swept out into the interplanetary medium. The rotation of the Sun produces the spiral pattern. The magnetic field near the Earth is measured to be rather uniform over large sectors of the Sun, corresponding to one dominant polarity or another. The solar-wind flow has a continual effect on the upper atmosphere of the Earth. *See also:* SPACE PROBE.

Coronal holes

Early coronal observations showed that the corona was occasionally absent over certain regions. In particular, at sunspot minimum it was quite weak over the poles. The x-ray images, particularly the long sequences from Skylab, revealed great bands of the solar surface essentially devoid of corona for many months. These proved to be regions where the local magnetic fields were connected to quite distant places, so the fields actually reached out to heights from which the solar wind could sweep the gas outward. The poles, of course, were the extreme case because the field lines reached out to the other pole of the Sun but were swept away by the solar wind. Analysis of solar-wind data showed that equatorial coronal holes were associated with high-velocity streams in the solar wind, and recurrent geomagnetic storms were associated with the return of these holes. Thus the relative intensity of the corona over sunspot regions is partly due to their strong, closed magnetic fields, which trap the coronal gas. Coronal holes are particularly prominent in the late stages of the sunspot cycle. There is usually a coronal hole at each pole, and more rarely coronal holes at lower latitudes.

Solar Activity

There are a number of transient phenomena known collectively as solar activity. These are all connected with sunspots.

Sunspots

Sunspots were discovered around 1610 independently by Johannes and David Fabricius, Christoph Scheiner, Galileo Galilei, and Thomas Harriot, and were sporadically observed afterward. For over 200 years they were thought to occur at random, until Heinrich Schwabe, who carried out regular observations in hopes of spotting a planet inside the orbit of Mercury, announced in 1843 that their number rose and fell with a 10-year period. Subsequent study of the old records revealed an 11-year period since the original discovery (**Fig. 12**).

The number of sunspots peaks soon after the beginning of each cycle and decays to a minimum in 11 years. The first spots of a number cycle always occur at higher latitudes, between 20° and 35° , and the latitude of occurrence decreases as the cycle unfolds (Spörer's law). Almost no spots are observed outside the latitude range of 5° – 35° . The great majority are small and last a few days, but some last for two rotations. In 1908, George Ellery Hale used the Zeeman effect to discover that sunspots had strong magnetic fields. Each spot group contains positive and negative magnetic polarity (monopoles are forbidden by Maxwell's laws). Hale found that the

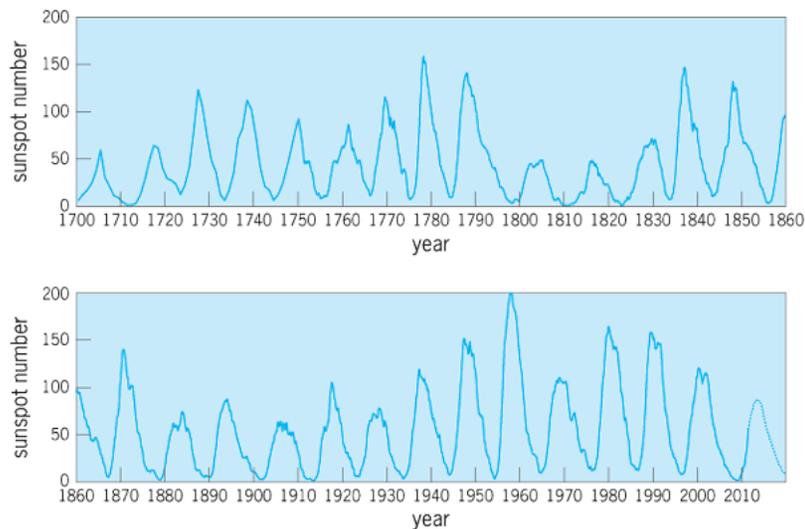


Fig. 12 Sunspot numbers from about 1700 to 2011, with extrapolation to a possible peak in 2013 and beyond that date. (D. B. Seaton; data from *Solar Influences Data Analysis Center, Royal Observatory of Belgium*)

polarities were mirrored, with the same polarity generally leading in one hemisphere and following in the other. He found that with each new number cycle the lead polarity switches, so that the complete magnetic cycle lasts 22 years. But each new number cycle starts a few years before the end of the previous one, so the average duration of a half-cycle is nearly 14 years. *See also:* MAGNETISM; ZEEMAN EFFECT.

The darkness of sunspots is probably due to the intense magnetic fields (3000 gauss or 0.3 tesla), which cool the surface by suppressing the normal convective energy flow from below. It takes several days for the darkening to occur. The average magnetic field in sunspot umbras, the darkest part of sunspots, has been measured during the 2000s, using new capabilities in the infrared, to be diminishing from 3000 to 2000 G (from 0.3 to 0.2 T), and it is thought that if the average field reaches only 1500 G (0.15 T), sunspots may no longer become visible.

Although sunspots are cool, their neighborhoods are scenes of the hottest and most intense activity, generally referred to as an active region. Magnetic energy is continually released there through reconnection processes of opposite magnetic fields. The corona above an active region is hot and dense, roughly three times hotter and denser than in quiet regions.

The birth of sunspots is marked by the appearance of pairs of small spots, separating rapidly at about 20,000 km (12,000 mi) a day. The motion is due to emergence of flux loops from below the surface, with the spots occurring at the intersection of the loops with the surface. In $H\alpha$, dark arches connect the members of a pair. Doppler shifts show the material at the top of the arches rising with them, while the gas pours down at the bottom of the arches. This must result from magnetic tubes pushing up from below. The p (leader) spot rapidly moves westward while the f (follower) spot remains fixed. This is true even if the spot of normal leader polarity is following. In most cases the f spot dies out, leaving a bright plage, while the p spot grows into a mature, round

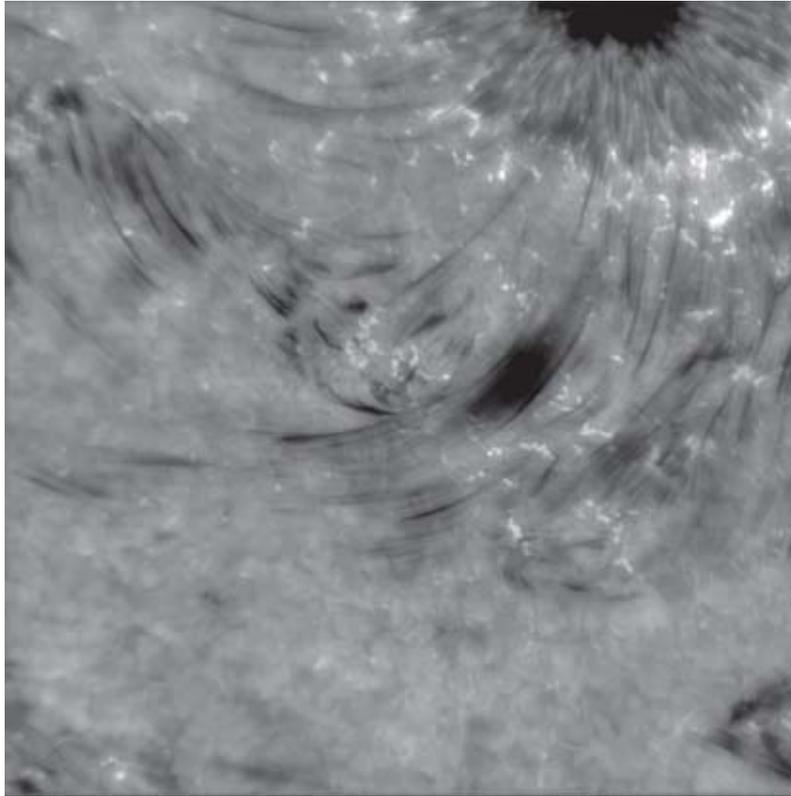


Fig. 13 A sunspot and the surrounding region photographed in $H\alpha$ light on July 1, 2010. In such a photograph it is not possible to see down to the granulation. At this higher level the matter is dominated by field lines that delineate the magnetic configuration. Outside the penumbra, we see jets moving at about 50 km s^{-1} (30 mi s^{-1}). (Big Bear Solar Observatory/New Jersey Institute of Technology)

spot (**Fig. 13**). If there are little spots around, they merge into the main p spot. After a few days the p spot stops separating, and the sunspots no longer move.

Often if the region is born with a tilt to the east-west line, the p spot will drag it into conformity with the rules. If an emerging spot group has the wrong polarity it usually dies out quickly, but once it reaches some size the p spot produces considerable activity as it plows through the other fields, and the group occasionally grows to be a particularly active region. When the sunspots form, the dark arches disappear, but they may remain at the center of the group to mark flux still emerging. The typical spot group grows in a few days to the configuration of p spot and f plage, lasts a week or two, and disappears, leaving two puddles of p and f magnetic fields marked by weak plages. Very large groups tend to be formed by the merging of smaller spot pairs (**Fig. 14**). As new flux pushes its way into old, great stresses and shears occur, which are relieved by flares.

A typical mature sunspot is seen in white light to contain a central dark area, the umbra, where the magnetic field is strong and vertical, surrounded by a less dark band called the penumbra, where the magnetic field spreads out radially, with gradually increasing downward tilt, forming an aura of dark fibrils across the granulation (**Figs. 15**

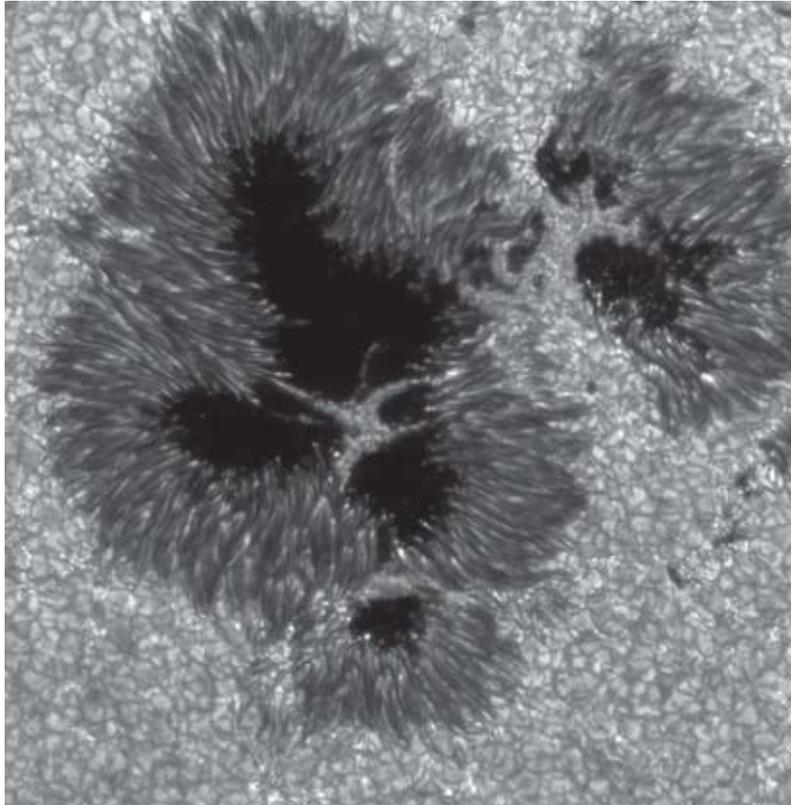


Fig. 14 A large sunspot group, photographed in visible light showing the filamentary structure of the penumbra and the granulation of the surrounding surface. (Royal Swedish Academy of Sciences)

and **Fig. 16**). The umbra is about 3000 K (5000°F), cool enough to form molecules. The pressure inside the spot, consisting of magnetic and gas pressure, must balance the outside pressure; however, the magnetic field has a steeper height gradient than the pressure, so it is impossible to balance at all heights. Therefore, strong outflows occur in the penumbra, called the Evershed effect. Alexander Wilson noticed in 1769 that when a spot is near the limb the penumbra is foreshortened, as if the umbra is depressed below the photosphere. Observations of the chromosphere above the sunspot reveal the presence of strong oscillations, called umbral flashes, with a 150-s period. In the penumbra, running waves spread radially outward with a period of 300 s, roughly twice that of the umbral flashes, and a velocity decreasing from 25 to 10 km/s (15 to 6 mi/s).

When the sunspots die out (a matter of days or weeks), some of the fields sink below the surface, and other fields break off and spread across the surface. These fields are concentrated in the edges of the chromospheric network, which has the same scale as in the quiet Sun but is much brighter in the chromospheric lines. Thus the supergranulation drives the distribution of the magnetic fields brought to the surface by the spots. While local fields are mixed and irregular, the huge spot fields form extended unipolar regions of enhanced polarity (**Fig. 17**). Because the poles rotate more slowly than the equator, the fields lag behind each sunspot group as they drift poleward, forming a butterflylike global pattern. The unipolar regions of following polarity gradually drift to the

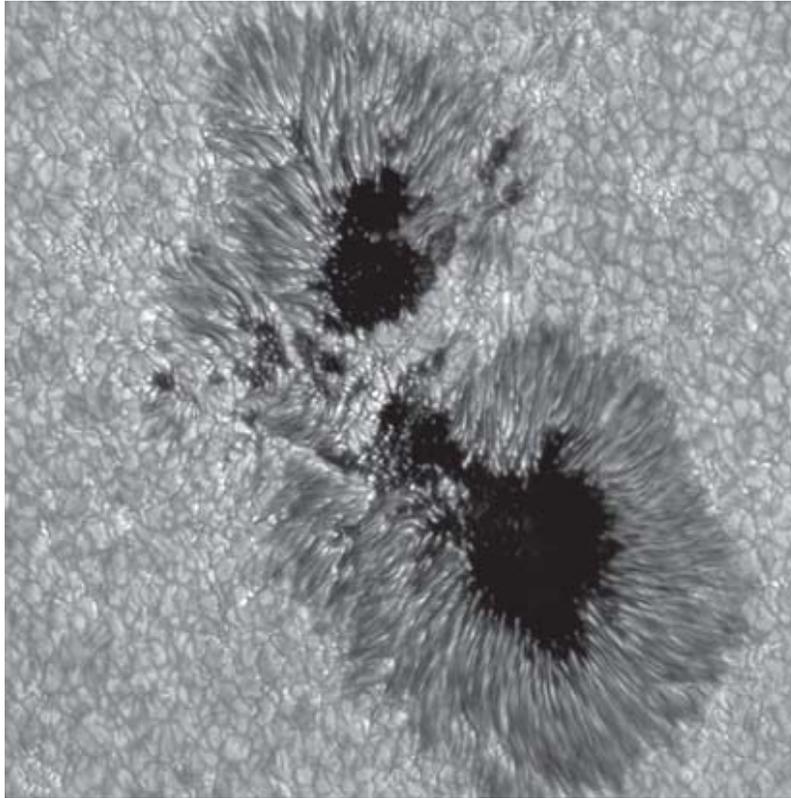


Fig. 15 A sunspot pair photographed in visible light with extremely high resolution on September 20, 2011, with the 1-m New Solar Telescope at the Big Bear Solar Observatory. The sunspot umbras are surrounded by penumbras, where fine fibrils mark the radial force lines. (*Big Bear Solar Observatory/New Jersey Institute of Technology*)

pole and establish a new dominant magnetic polarity. The new field is that of the following spots, opposite to the polarity of the preceding sunspots that dominate most spot groups. There is some evidence that a meridional poleward flow is responsible.

This process reverses the polar magnetic fields every 11 years, and with it the interplanetary fields that the solar wind carries out from the Sun. Some models of solar activity propose that, as the sunspots of the parent cycle die away, this large-scale dipole field is amplified by the differential rotation to produce a new cycle of sunspots, opposite in polarity to the preceding one.

The large unipolar magnetic regions spreading out from centers of activity are easily recognized on $H\alpha$ or calcium monochromatic pictures of the Sun because they are particularly bright. Their boundaries are usually marked by large prominences, accumulations of material in the atmosphere supported by the horizontal field. These are seen as dark filaments (**Fig. 6**).

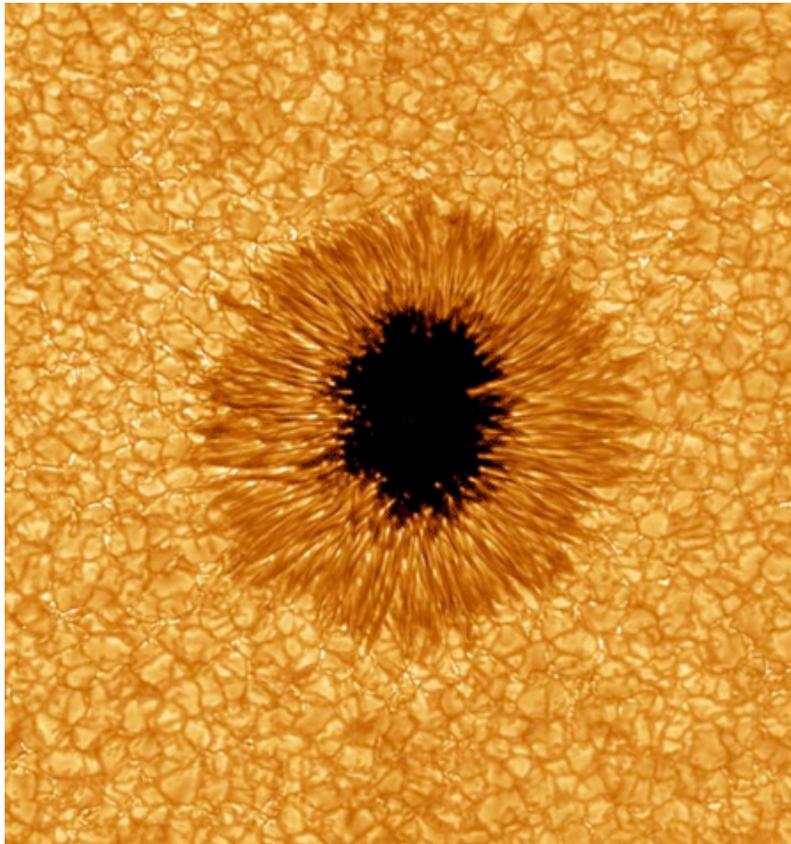


Fig. 16 A symmetric sunspot with its dark umbra and lighter fibrils of its penumbra, on a background of solar granulation. Bright filigree is seen threading its way through some of the dark lanes between granules. The umbra and penumbra together are about the same size as the Earth. (*Big Bear Solar Observatory/New Jersey Institute of Technology*)

Evolution of weak fields

According to Maxwell's laws, there are no individual magnetic monopoles, and all fields must be connected to an opposite pole. The fields that can be seen represent the intersection with the surface of flux loops making this connection. Above the surface, their form can be judged from x-ray images, while below they are tied to an unknown driver. The magnetic fields involved must last for years, surviving turbulent flows. How this happens is not known, but two important processes affect their evolution. First, there is the frequent emergence of small dipoles known as ephemeral active regions. These dipoles are as strong as the network elements, and separate until one branch encounters a network element of the opposite polarity, whereupon they recombine and disappear, leaving the opposite branch. At the same time, many very small intranetwork fields of both polarities emerge near the cell centers and are swept to the boundaries, but their effect on the network is mixed, and the processes generating them are unknown.

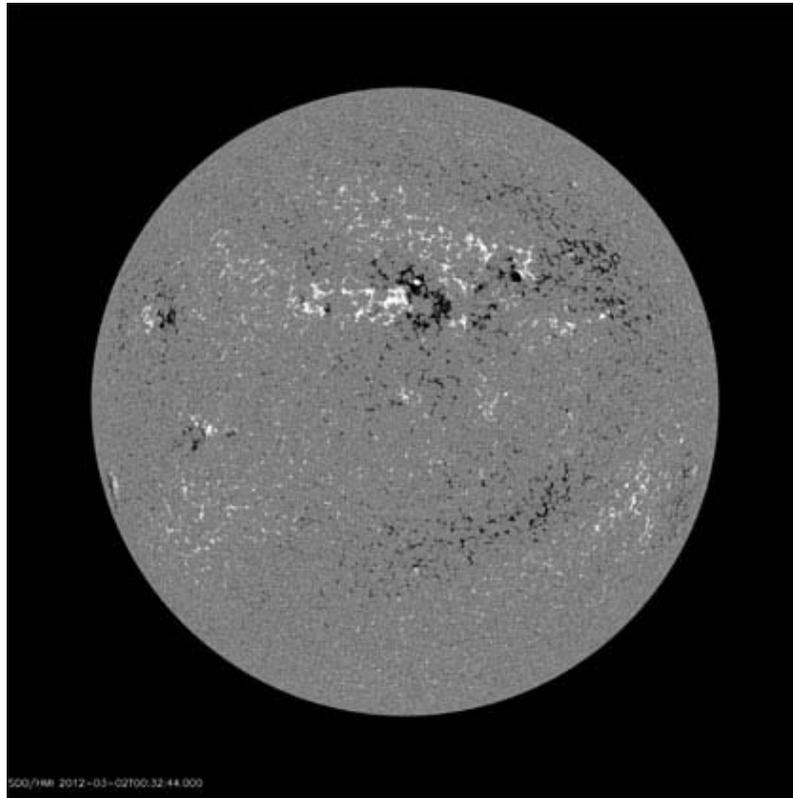


Fig. 17 Distribution of magnetic fields on the Sun at a time of rising solar activity (March 2, 2011), taken with the Helioseismic and Magnetic Imager (HMI) on NASA's Solar Dynamics Observatory (SDO). It matches the composite color image on Fig. 8. Black areas are regions where the magnetic field points away from the Earth; white areas, toward the Earth. The strength of the field is indicated by the degree of blackness or whiteness. The north rotation pole of the Sun is at the top. (Stanford Lockheed Institute for Space Research/HMI/NASA)

Prominences

The term “prominence” is used for any cloud of relatively cool gas in the corona, where it appears bright against the sky. They have roughly chromospheric temperatures and so are also especially well seen in the spectral lines of hydrogen. Because these clouds absorb the chromospheric light and scatter it, they appear dark against the solar disk in $H\alpha$ and other strong lines. In continuous light they are transparent. At the limb we see the chromospheric light they scatter against the dark sky. Since they are much denser than the corona, something must hold them up against gravity. Prominences are found only in regions of horizontal magnetic fields that support them. Thus filaments on the disk, which may last for weeks, are good markers of the magnetic boundaries. When the magnetic structure changes, prominences become unstable and erupt, always upward (**Fig. 18**). They also may be ejected by solar flares or appear as graceful loops raining from the corona after flares. The fact that prominences never fall down to the solar limb testifies to their magnetic support. The gas is ionized and cannot fall through the horizontal fields. The spectra of prominences show a number of bright emission lines of various elements, mostly singly ionized. Analysis of these lines shows that long-lived, stable prominences have

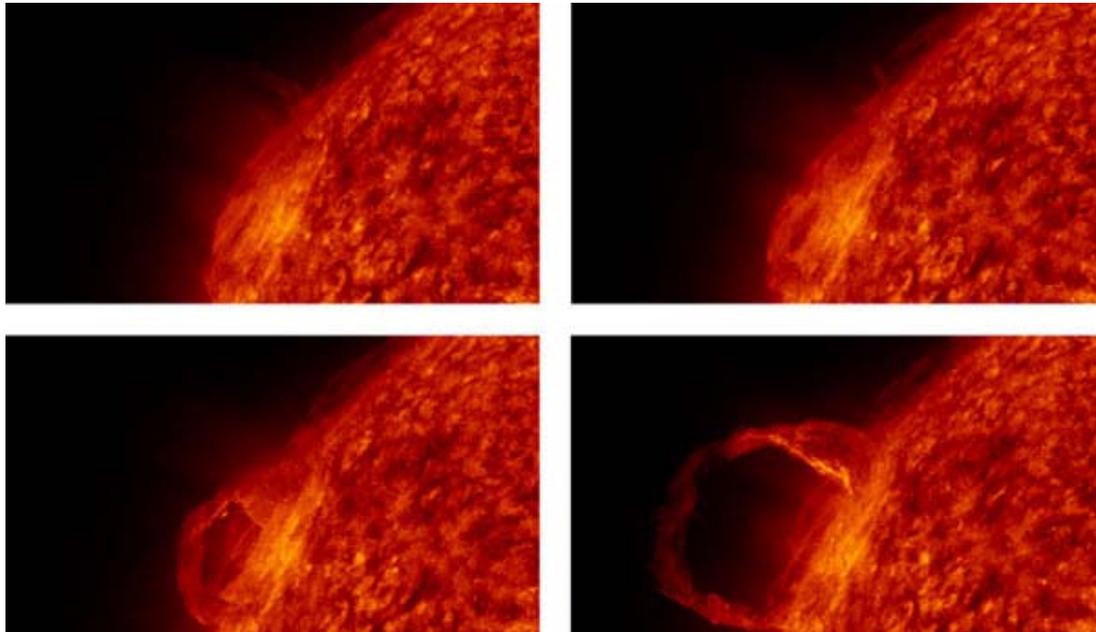


Fig. 18 Large prominence in its eruptive phase after days or weeks of static inactivity, seen through a filter that passed only the 30.4-nm radiation of helium with the Atmospheric Imaging Assembly of NASA's Solar Dynamics Observatory (SDO). The horizontal width of a single frame is about 200,000 km (125,000 mi). (NASA's Goddard Space Flight Center Scientific Visualization Studio)

a temperature of about 4000 K (7000°F), while transient prominences condensing from flares show many fewer lines and are more than 30,000 K (54,000°F).

Plages

Just as prominences occur when the magnetic field changes from one sign to the other, plages occur whenever the magnetic field is vertical and relatively strong but not strong enough to form a sunspot. They are bright regions in any strong spectrum line, because the chromosphere is heated there (Fig. 6). If the field is horizontal, there is no heating; the upward flow of energy is suppressed. Some scientists believe that the field is stable only when it exceeds 500 gauss (0.05 tesla), and the apparent field is only the density of clumps of strong field. In a typical active region, the preceding magnetic field is clumped in a sunspot and the following field spread out in a plage. In $H\alpha$ light, the plages are seen to be connected to the sunspot by dark fibrils outlining the lines of force. Since the magnetic fluxes must be equal, the fields in plages are related to those of the spots by the ratio of their areas. Plages are bright in almost all wavelengths: x-ray, radio, and ultraviolet. But in the corona as seen in x-rays and ultraviolet emission lines, the peak brightness and temperature are at the arch tops, farthest from the cooling effects of the surface. The elements of the chromospheric network resemble small plages.

Although sunspots are always accompanied by plages, the reverse is generally not true. Occasional fields of small plages develop in the sunspot zone and fade away without the appearance of any spots. In these cases the magnetic fields never reach sufficient strength to generate sunspots. The plages usually remain for a few weeks to mark the location where a sunspot has died. Eventually they break up and spread out into the chromospheric network. In the stronger parts of that network, tiny spots have been noted.

Flares

The most spectacular activity associated with sunspots is solar flares (**Fig. 19**). A flare is defined as an abrupt increase in the $H\alpha$ emission from the sunspot region. Flares were first observed in white light and $H\alpha$, which can be observed on Earth, but are now often classified in terms of their brightness in x-rays or extreme-ultraviolet (EUV) radiation. The brightness of a flare in $H\alpha$ may be up to eight times that of the chromosphere; the rise time is seldom longer than a few minutes. The $H\alpha$ brightening results from heating of the chromosphere at the footpoints of the magnetic field by a tremendous energy release in the atmosphere, resulting from the energy stored in the local magnetic field. While flares are most readily visible from ground-based telescopes in chromospheric lines, the footpoints of big flares can be seen in white light. From the footpoints, now much better studied from *SDO* than from ground-based telescopes, a cloud of hot material, up to 3×10^7 K (5.4×10^7 °F) arises and concentrates at the arch tops. This cloud condenses out in an array of loop prominences. An active sunspot group produces a hierarchy of flares, a few large and many small ones. The distribution is a power law: the energy released in the three or four greatest flares equals that in all the small flares put together. Flares are generally ranked by the peak soft x-ray flux as measured by the Geostationary Operational Environmental Satellites (GOES) and classified by the National Oceanic and Atmospheric Administration (NOAA). The classes are A, B, C, M, and X, depending on whether the 0.1–0.8-nm peak flux is 10^{-8} , 10^{-7} , 10^{-6} , 10^{-5} , or 10^{-4} W/m² at the Earth. Finer differences in flare strength are indicated by a number following the flare class letter; thus, X2 has a flux of 2×10^{-4} W/m². The duration, unfortunately, is ignored.

While the lower-energy manifestations of a flare are seen, all evidence is that the original energy input is in nonthermal particles. The soft x-ray flux has been shown to be the time integral of the degraded hard (greater than 40 keV) electrons, which produce the hard x-rays. So the GOES index is a fairly good measure except in the case of long-duration events. Solar flares also accelerate electrons and ionized atoms (including protons, which are ionized hydrogen) to speeds close to the speed of light. Neutrons also result, from interactions of protons with helium nuclei (which, for historical reasons, are known as alpha particles). There is wide consensus that the energy needed to drive flares is released by the process of magnetic reconnection, in which the topology of highly stressed or jumbled magnetic field lines in the corona rapidly changes, resulting in new field configurations with lower energy. The excess energy released by this process is enough to generate a flare and accelerate an associated CME (**Fig. 20**). This process, and the flares that accompany it, are often associated with the eruption of filaments. Usually the filament, which separates the preceding and following fields in an active region, is destabilized and erupts outward. A few minutes after the eruption begins, there is an abrupt

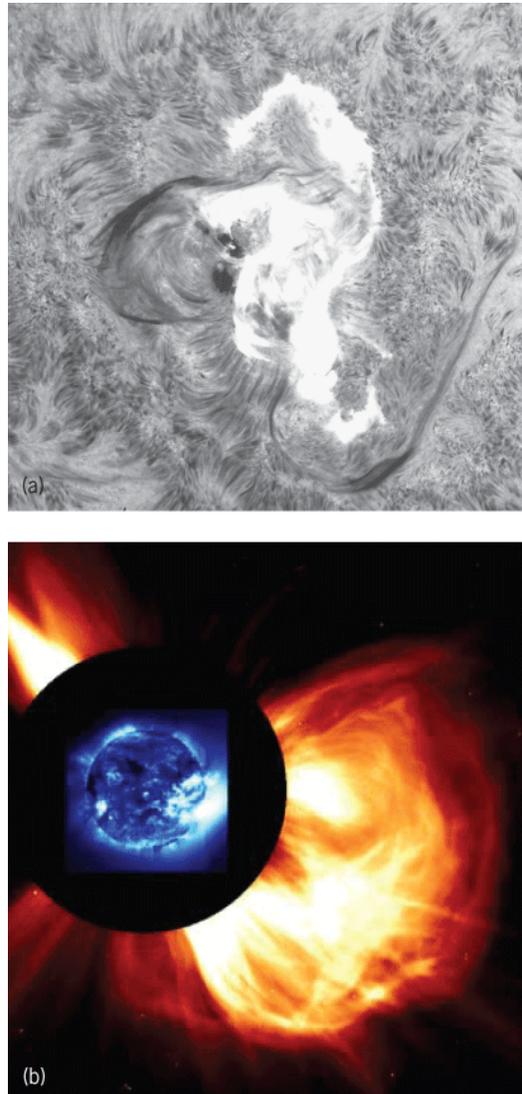


Fig. 19 Solar flares (a) The great “sea horse” flare of August 7, 1972, late in the flare, photographed in the blue wing of the $H\alpha$ line. The neutral line between two bright strands (“ribbons”) is crossed by an arcade of bright loop prominences raining down from the corona. (*Big Bear Solar Observatory/then California Institute of Technology/H. Zirin*) (b) Composite image of the solar flare and coronal mass ejection of November 4, 2003, as observed by the Extreme-ultraviolet Imaging Telescope (EIT) [inner region] and Large Angle Spectroscopic Coronagraph (LASCO) C2 [outer region] instruments on the Solar and Heliospheric Observatory(SOHO) spacecraft. (*EIT/SOHO and LASCO/SOHO Consortia, ESA, and NASA*)

acceleration and a storm of energetic particles is produced, heating the corona to flare brightness. When filaments not connected with active regions erupt, the brightening is much less. Filament eruptions, primarily those just preceding flaring, are apparently the source of coronal mass ejections. Because the activation of coronal mass ejections often precedes the flare brightening, some have concluded that these ejections produce flares, but they are both aspects of the same occurrence.

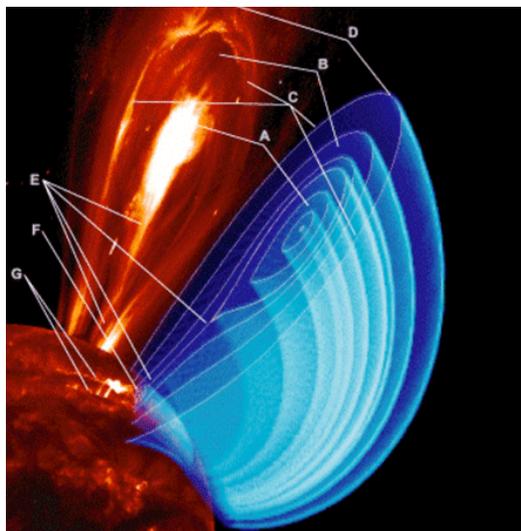


Fig. 20 Composite image of a two-ribbon flare and a cross section of a coronal mass ejection (CME) as observed by the SOHO spacecraft (the CME image is offset from the flare image for clarity). The diagram depicts the inferred magnetic field structure according to the theoretical model of J. Lin and T. G. Forbes. The coronal mass ejection comprises (A) the driver gas, (B) the dark void, (C) the outward-moving bright bubble, and (D) the shock front. The (E) current sheet, (F) arcade of magnetic field loops, and (G) their footpoints, which form the two-ribbon flare, also are shown. (After A. Panasyuk, *Harvard-Smithsonian Center for Astrophysics, and LASCO/SOHO Consortium*)

Because of the terrestrial effects of flares, it is important to understand in which active regions they are most likely. Originally it was thought that the large sunspot groups were the source, but H. Künzel in 1965 defined a new class, δ -spots, where two umbrae of opposite magnetic polarity are encased in the same penumbra. These spots are responsible for almost all large flares. This property shows that solar flares are a magnetic phenomenon. Normal dipoles are separated, like the poles of a bar magnet, but the umbrae of a δ -spot are pushed up against one another. The field lines twist into the boundary and often support a filament. It takes a good deal of energy to push the poles together, and some of this energy is released in the flare through magnetic reconnection.

These complex magnetic fields occur as the result of sunspot motion or emergence. When new spots emerge in an active region, steep gradients are set up that eventually are released in the flare cataclysm. This scenario is especially true when the preceding sunspot speeds forward in its rotation, pulled by unseen forces below the surface. If the emergence is into like polarity, little will happen. But if the field into which it runs has opposite polarity, steep gradients will be set up. In some ways the δ -spot is like a magnetic black hole. The umbrae usually disappear locked together. While big spots will not necessarily produce big flares, big δ -spots produce the biggest flares.

Flare emissions. The flare produces a huge stream of solar energetic particles (SEP) as well as shock waves. The flare explosion produces a huge magnetohydrodynamic shock wave that flies out at least as fast as 1000 km/s (600 mi/s) and continues into interplanetary space, often reaching the Earth. The wave produces a huge radio

burst in the meter-wavelength range as it excites the coronal layers. The energetic nuclei produce gamma-ray lines from nuclear reactions as they penetrate to the photosphere. If they are sufficiently numerous, they heat the photosphere faster than it can reemit energy and a white light flare is observed, usually in the form of bright transient flashes at the foot points of the flare loops. The particles reach the Earth in a great particle storm. The SEP can be hazardous to spacecraft and, potentially, to astronauts, and are a major limitation that must be considered in planning long voyages, such as to Mars from Earth. *See also:* SHOCK WAVE.

Two classes of such storms are observed. In one, the nuclei show stages of ionization common in the corona such as Fe^{+13} , suggesting that they have been swept up by the shock wave in the corona. Solar storms in the other class are more impulsive and include ions from the flare itself, such as Fe^{+23} , so highly ionized that the temperature must be in the vicinity of 20 million kelvins. Particles from such storms also show a huge overabundance of the helium-3 isotope. Usually helium-3 is several thousand times less abundant than helium-4, but in these events it can reach parity. The acceleration of helium-3 must take place in the flare itself. The nuclei, along with hard and soft electrons, produce the optical event seen in the chromosphere.

Electrons radiate a range of photons as they interact with atoms and magnetic fields. When they collide with protons, they produce hard x-rays by bremsstrahlung. The first, impulsive burst of electrons is hard, and so are the x-rays produced, with a nonthermal power-law spectrum up to the gamma-ray range. As these degrade by collisions, a softer, thermal spectrum is produced. Even if there are no field particles, they can produce microwave radiation by synchrotron emission as they spiral in the magnetic fields. From the spectrum of the microwaves and x-rays, the number and spectrum of the electrons can be deduced. With huge radio antennas and arrays such as the Jansky Very Large Array (JVLA) in New Mexico, the radioheliograph in Nobeyama, Japan, and the Chinese Spectral Radioheliograph that is being constructed in Inner Mongolia at the Mingantu Observatory (an expanded version should be operable in 2013), the source of microwaves can be mapped. Even higher resolution was attempted with the JVLA by time-differential measurements during the May 20, 2012, annular eclipse in which the Moon covered several active regions. Not surprisingly, microwaves come from the end of the flare loop with the strongest magnetic field, while x-rays come from the densest part of the loop. *See also:* BREMSSTRAHLUNG; RADIO ASTRONOMY; RADIO TELESCOPE; SYNCHROTRON RADIATION.

When the filament at the site of the flare heats up, a coronal cloud is formed with a temperature above 3×10^7 K, 10 times hotter and 100 times denser than the normal corona. This cloud is confined by magnetic effects and produces strong soft x-rays and ultraviolet emissions. This emission is full of spectrum lines, due to highly ionized atoms all the way up to Fe^{+25} (iron with all but one of its electrons stripped away). In the first stages of the thermal event, the Fe^{+25} and Fe^{+24} lines are seen; then as the plasma cools down, lines of elements in lower ionization dominate, along with iron in lower ionization states. Oddly, the lower ionization stages are not seen as the corona heats up. The line intensities have different density and temperature dependences, and the intensity ratios are used to deduce the local density, the temperature being given by the ionization.

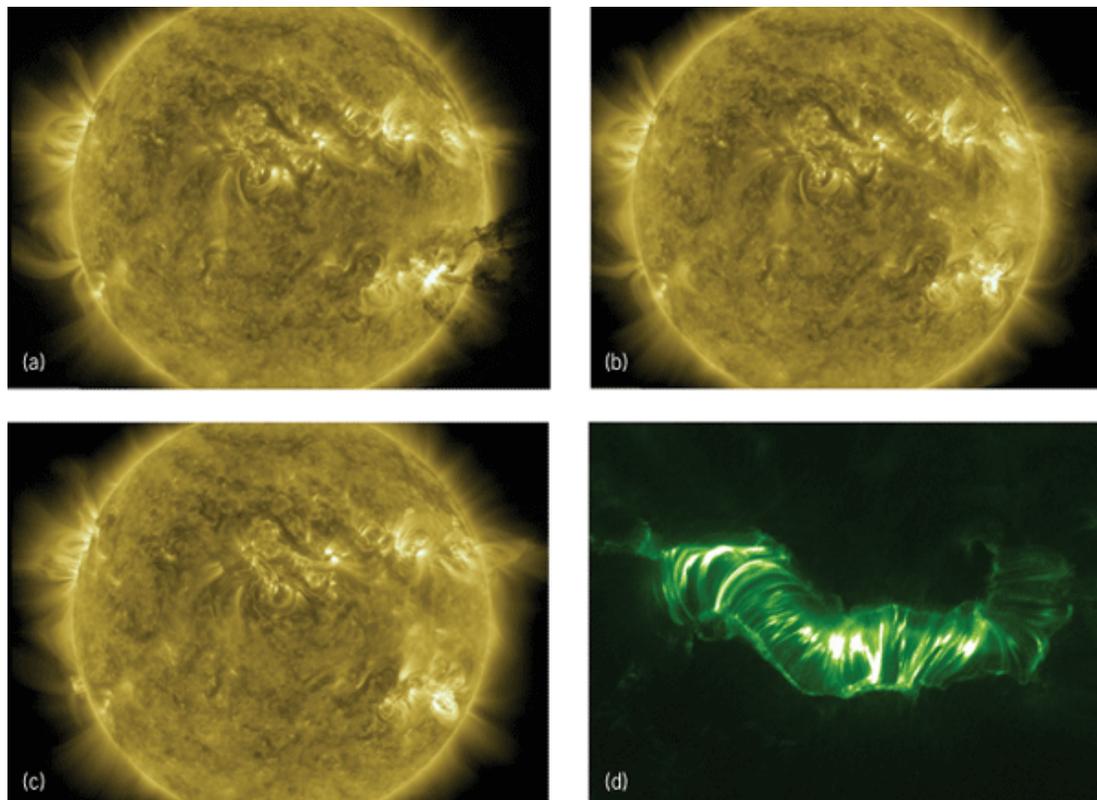


Fig. 21 A flare erupts near the lower-right edge of the Sun's visible disk, as seen with the Atmospheric Imaging Assembly of the Solar Dynamics Observatory (SDO). (a) The flare erupts, and cooler material falls back and absorbs radiation from the background. (b) Small postflare loops of hot gas form across the magnetic neutral line. (c) A stage minutes later with larger postflare loops. (d) In another flare, imaged with NASA's Transition Region and Coronal Explorer (TRACE) satellite, an arcade of loops crosses a neutral line in the magnetic field. TRACE is a predecessor to SDO with the same resolution but a smaller field of view. Lower-resolution observations than the ones displayed might seem to show the overall path as a loop of gas, while the high-resolution observations show that the loops are, in fact perpendicular to the larger-scale phenomenon. (Lockheed Martin Solar and Astrophysics Laboratory/Smithsonian Astrophysical Observatory/NASA's Goddard Space Flight Center Science Visualization Studio/NASA)

Flare ejecta. Almost every flare is accompanied by the ejection of material; the magnetic field acts like a rifle barrel to collimate the flare energy. Neutral hydrogen in the flare filament is usually ejected in a poorly collimated spray (Fig. 21) at speeds typically a few hundred kilometers per second. Higher speeds, 1500 km/s (900 mi/s) have been recorded, and the fastest coronal mass ejection so far recorded was 3200 km/s (2000 mi/s). The sprays give rise to a magnetohydrodynamic shock wave in the corona that may be recognized in meter-wavelength radio emission by a type II or slow-drift burst. As the wave moves to lower densities, the radio emission excited drifts downward in frequency. The wave velocity is 1000–2000 km/s (600–1200 mi/s), and the waves have been observed all the way out to the Earth. The waves carry energetic trapped particles, and a large increase in low-energy cosmic rays (1–5 MeV) is often observed when the wave reaches the Earth.

Flare waves are often observed on the solar surface in $H\alpha$ light when their path is such as to include the surface. They usually appear as a bright front; sometimes filaments wink (that is, they drop out of the $H\alpha$ bandpass by a down-and-up Doppler shift) as the front goes by. When seen in the chromosphere, such waves are called Moreton waves. Observations in the EUV have revealed that Moreton waves have a faint counterpart in the corona as well. The flare wave is thought to be the accelerator of coronal material into solar energetic particles.

Space-based EUV telescopes have also revealed the existence of another type of wave that propagates through the corona more slowly than a Moreton wave. These waves are referred to as EIT (for the telescope that discovered them, the Extreme-ultraviolet Imaging Telescope on SOHO) or EUV waves. These waves expand circularly out from the site where an eruption originated and are the leading edge of large areas of dimming that often accompany eruptions. EIT waves are believed to be the point at which the leading edge of an approximately spherically expanding eruption intersects the low corona.

There is a whole range of jetlike ejecta called surges, which may be quite large. They usually occur in the vicinity of large sunspots where the magnetic field is strong enough to contain and collimate the material. Surge velocities are usually less than 200 km/s (120 mi/s), and the surges often fall back along the same route that they initially traveled.

Space-based coronagraphs can detect events in the corona around the clock. They observe many coronal mass ejections, which occur roughly three times a day and are important players in solar-terrestrial connections. The addition of the coronagraphs on NASA's STEREO mission, with their views from vantage points substantially around the Earth's orbit, complement the space coronagraph on SOHO to show the entire Sun at all times, meaning that no flare now goes undetected.

Solar-terrestrial effects

The Earth is immersed in the solar wind and the magnetic fields streaming out from the Sun. It is shielded from the particles by its magnetic field, and the surface is shielded from ultraviolet and x-ray photons by the upper atmosphere. As complex worldwide systems are developed, the effects of the Sun on the Earth become more significant, especially on activities above these protective regions. The energetic particles can penetrate the magnetic field at geomagnetic latitudes around 65° (the magnetic pole is somewhat displaced from the true pole of rotation), leading to a magnetic reconnection between the Earth's magnetosphere and the solar particles. This region is called the auroral belt because particles coming in from the Sun produce frequent aurora borealis (northern lights) there, as well as aurora australis (southern lights) at the corresponding southern latitudes. The most energetic photons are absorbed in the upper atmosphere of the Earth above 70 km (42 mi) in a layer termed the ionosphere. Radio waves below 10 MHz frequency are reflected by the ionosphere, making possible intercontinental radio communication, but high levels of soft x-rays from flares increase the ionization in the lower ionosphere to the point where the waves are absorbed instead of reflected. The solar ultraviolet emission at longer wavelengths produces the ozone layer, which in turn absorbs that radiation and keeps it from reaching

the ground. If ozone is destroyed, the solar radiation produces more. The radiation in question varies by 2–3% in a solar cycle, producing modest changes in the ozone. While communications utilizing direct high-frequency satellite links are unaffected by the ionosphere, systems such as the Global Positioning System require such sensitive timing that their position determinations are distorted by solar-produced fluctuations in the ionization of the atmosphere. Satellites in low Earth orbits are strongly affected by changes in the height of the outer atmosphere, which varies as it is heated by ultraviolet radiation and particles from the Sun. Thus, high levels of sunspot activity can bring about premature decay from orbit. *See also:* AURORA; IONOSPHERE; MAGNETOSPHERE; RADIO-WAVE PROPAGATION; SATELLITE NAVIGATION SYSTEMS.

Geostationary satellites may be aligned directly with the Sun twice a year, and if the Sun is particularly active, they can be useless for a few days. Other satellites depend on local magnetic fields for orientation and must be shut off during disturbed periods. Some satellites have been disabled by flare x-ray bursts. SDO relays its observations to Earth using a geosynchronous satellite that is always in view from the ground station in New Mexico except for very occasional Sun alignments. *See also:* COMMUNICATIONS SATELLITE; SPACE COMMUNICATIONS.

Geomagnetic storms. The most spectacular effects are caused by geomagnetic storms, the invasion of the magnetosphere by clouds of solar particles from flares, coronal mass ejections, and coronal holes. The great solar-terrestrial events are typically caused by huge flares in large convoluted active regions. The “big flare syndrome” refers to the fact that these events produce almost every one of the various effects discussed above. In particular, the large shock waves associated with type II bursts are considered a likely source of particle acceleration. The absence of energetic particles from flares far behind the solar limb suggests that the main particle acceleration occurs fairly low in the solar atmosphere. X-rays from flares also are produced low in the atmosphere.

The cosmic-ray storms produced by big flares do not reach the equatorial regions easily because of the Earth’s magnetic field, but they spiral into the polar caps and produce polar-cap absorption (PCA). This effect is the direct ionization of the ionosphere above the poles, and it results in a blackout of radio communications across the polar regions. The very large number of particles associated with the low-energy pulse manages to penetrate the geomagnetic field to produce the geomagnetic storm. Such storms are most intense near the poles, but may reach down into temperate and even tropic latitudes. The aurora is but one trace of the energetic particles precipitating in the upper atmosphere. The currents around the Earth induced by these great numbers of particles produce sharp changes in the Earth’s magnetic field, and the ionization produces considerable changes in the radio propagation. The magnetic fluctuations generate large voltages in long conductors such as power transmission nets and telephone lines. For example, sharp voltage changes in long-distance power transmission lines during a large geomagnetic storm a few days after a spectacular flare on March 10, 1989, fired circuit breakers in the Hydro-Quebec network and left Montreal without power for days. The same induced voltages disturb the logging of oil wells and other devices depending on voltages in long conductors. *See also:* GEOMAGNETIC VARIATIONS.

The relation between geomagnetic storms and flares is not completely determinate. Large flares on the western side of the Sun usually produce the most geomagnetic disturbances, normally by initiating a coronal mass ejection by filament eruption. The passage of a large coronal hole across the disk of the Sun normally initiates a magnetic disturbance without a coronal mass ejection. Because the solar wind escapes the coronal hole area easily, high velocities are attained, which produce predictable storms. Since the big coronal holes return several times, they cause 27-day recurrent geomagnetic disturbances termed M-region storms. Series of 10 such storms have been detected near the end of the sunspot cycle. Spacecraft measurements have shown a close connection between coronal holes and high-velocity streams. The largest geomagnetic storms, however, are produced by the shock waves and coronal mass ejections from big flares. Energetic particle events are not always associated with geomagnetic storms.

It is not possible to predict the occurrence of great sunspots. However, once a group is seen, the likelihood of its producing substantial flares can be predicted over several days. This is done by evaluating the magnetic configuration, the degree of magnetic field shear, the existence of a δ configuration, and other parameters.

Substorms. Observations of the aurora have identified a smaller phase of the geomagnetic field called the substorm. A substorm is a violent rearrangement in the outer fringes of the Earth's field, where it interacts with the solar wind and is drawn out into a long tail on the antisolar side. It has been found that substorms tend to occur when the north-south component of the magnetic field in the solar wind changes from parallel to antiparallel with the Earth's field.

Many scientists believe there is a link between the sunspot cycle and long-term weather trends, but it has proved very difficult to detect. Between 1650 and 1715 there were very few spots, and there is persuasive evidence for a Little Ice Age during this period, known as the Maunder minimum. This event shows that the cycle may not necessarily always produce spots, but as a single event it does not prove much. There was a remarkable coincidence between alternate (22-year) sunspot minima and droughts in the Great Plains of the United States in 1910, 1932, 1954, and 1976. Droughts are so sporadic, however, that direct statistical connections are not very obvious. For example, 1980 was a year of heat and drought too, but at the maximum of the sunspot cycle. However, some analyses show that the likelihood of severe local droughts does peak at the 22-year minima, but the locality of the drought will move about. Measurements of isotope ratios in fossil water, which indicate the temperature at which the water fell as rain, also show evidence of 22-year periods.

It has been proposed that galactic cosmic rays ionize particles in the upper atmosphere and produce condensation nuclei for rainfall. During sunspot maxima the solar fields expand beyond the Earth and shield against galactic cosmic rays, so there is less rainfall then. However, this theory directly contradicts the observation of great plains droughts at sunspot minima.

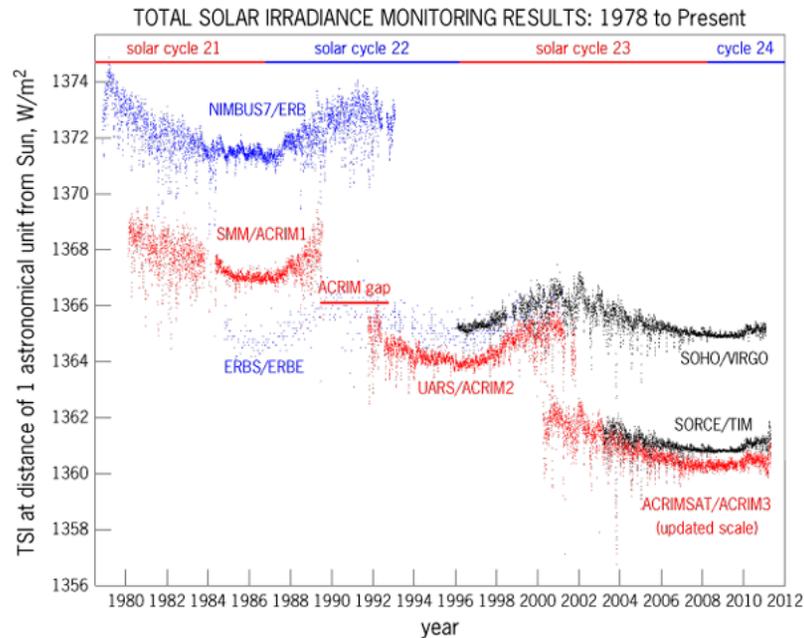


Fig. 22 The total solar irradiance (TSI) as monitored from space by various spacecraft and instruments aboard them. There is some minor disagreement in absolute calibration, as shown by vertical displacements in the curves, but the relative shapes are secure. The hoped-for calibration from NASA's Glory satellite disappeared with its unsuccessful launch in 2011. Note the periodic variation by about 0.1% over the sunspot cycle and the effects of sunspots causing dips at solar maximum, which otherwise corresponds to the maximum TSI. (Richard Willson, ACRIM.com)

Total Solar Irradiance

Through the early twentieth century, Charles Greeley Abbot tried to measure the amount of solar energy reaching the Earth's surface, taking into account clouds and other absorption in the atmosphere. He found variations of up to 10% in the so-called solar constant. But with the measurements of the total amount of energy reaching the Earth with the Advanced Cavity Radiometer Irradiance Measurement (ACRIM) on the Solar Maximum Mission, it became clear that Abbot's measurements had been faulty and that the energy reaching the Earth varied systematically. It is, therefore, now known as the total solar irradiance (TSI), and it is being monitored by several satellite instruments, notably VIRGO on SOHO, ACRIM3 on ACRIMsat, and TIM (Total Irradiance Monitor) on the SORCE (Solar Radiation and Climate Experiment) satellite (**Fig. 22**).

Notably, TSI is highest at sunspot maximum, though it diminishes with the passage of large sunspots. It declines by an average 0.1% over the solar cycle, with less variation appearing at solar minimum because of the absence of sunspots.

Solar Instruments

Two factors dominate all astronomical observations: seeing and transparency. Seeing is the disturbance of an image by atmospheric turbulence, which, for the Sun, blurs different regions so their physical properties cannot be distinguished. Transparency is more obvious, but often a clear but windy day produces images so blurred that observations are impossible. While the Sun is very bright, the use of high magnifications requires some attention to transparency. Because of the disturbance of the Earth's atmosphere by solar heating during the day, the seeing is considerably worse in the daytime, and without adaptive optics, Earth-based solar telescopes cannot hope to obtain images as sharp as those obtained with stellar telescopes.

Seeing is never perfect, and there are very few locations where excellent definition is possible during perhaps 100 h in a year. It is possible to find sites where reasonable images can be obtained much of the time, but there is no clear test for good sites other than empirical comparative measurement. For example, Mauna Kea is a superb site for nighttime observation, but when the Sun beats down on its black slopes, it is quite inferior. Results from measurements with shadow band detectors suggest that the best sites are at mountain lakes, high enough to attain clear air and surrounded by cool water.

Once a site is chosen, telescopes must be designed so that the great heating produced by the Sun does not distort the images. This is usually done by liberal use of white paint and careful control of the atmospheric conditions inside the telescope, sometimes by evacuating the interior.

Solar telescopes fall into two general classes: those designed for observations of the brilliant solar disk, and specialized instruments with low polarization or low scattered light, to study the much fainter prominences and the still fainter corona.

Disk telescopes

Excellent definition in a solar image of reasonable size is usually the first requirement in a disk telescope. Definition is limited by the quality of the optical system, the diffraction limit corresponding to the aperture, and the quality of the detector. Because solar phenomena are dynamic, the instruments must be rugged and capable of long, uninterrupted operation. Because the occurrence of exciting activity is unpredictable, the instruments should not require a great deal of adjustment to operate.

The telescope optical system must be guarded against air currents resulting from solar heating, as well as distortion of the optics. A lens absorbs little heat (light losses are due to reflection), but an aluminum mirror may absorb 10% of the light in heat, and requires a folded, hence longer, path. When chromatic aberration is not a consideration, a refractor is a good solution; the lens acts as a cap against thermal convection and the path length is short. An achromatic lens has the drawback that the components change differently with heat, and the focal

length is the difference between two large numbers. Since much solar work is monochromatic, the singlet refractor is ideal.

For large aperture and broad wavelength coverage, reflecting telescopes are required. Because the mirror absorbs heat and the light travels up and down the tube, the air must be removed from the tube and a vacuum provided, as well as large entrance windows, in order to obtain acceptable images. It is also possible to fill the tube with helium, which has a refractive index near that of vacuum. Special cooling is used to reduce changes in the mirror, and the Gregorian design is preferred because heat load on secondary optics is reduced. With proper care, the large reflector can do very well, but great care is required to cool the window.

R. H. Hammerschlag introduced a tubeless and domeless telescope that seems to give good results. Since the light passes through kilometers of air, the short extra path through the telescope should not interfere. However, without a dome, wind shake becomes a serious problem and careful design is required.

A popular type of disk telescope is the solar tower. Two flat mirrors at the top of a tower, one of which is equatorially mounted to follow the diurnal motion of the Sun, reflect sunlight into a long-focus fixed vertical telescope. The telescope may be either a refractor or a compound reflector of 30–50-cm (12–20-in.) aperture. It produces a large image of the Sun near ground level, where the light can be conveniently reflected into any one of a number of large fixed accessory instruments. The drawback of this design is the introduction of polarization by the mirrors, and seeing introduced by the mirrors if they are not in the vacuum.

For many purposes an equatorial telescope is preferred; in particular, it is easier to evacuate an equatorial system than a large tower, and for some purposes, such as polarimetry, a straight-through system is desirable. However, it is difficult to servo-guide an equatorial, because the whole telescope must be moved instead of a single mirror.

Though it has usually been thought that the Sun is so bright that solar telescopes did not have to be very large, the extreme slicing and dicing of the incoming solar beam for high-spatial-resolution, high-spectral-resolution observations has led to the design of the Advanced Technology Solar Telescope, to be built at Haleakala, Maui, Hawaii. Its 4-m (157-in.) mirror with an off-axis Gregorian configuration is to be on an alt-azimuth mount. Coudé and Nasmyth foci are to be available, and first light is hoped for in 2018. Five first-generation instruments are planned. They are a Near-Infrared Spectropolarimeter at the Nasmyth station, and, at the coudé focus, a Visible Light Broadband Imager, a Near-Infrared Spectropolarimeter, a Visible Spectropolarimeter, and a Visible Tunable Filter.

Several systems are in place for continual monitoring of the solar disk. The Global Oscillation Network Group (GONG) has a series of telescopes placed around the world so that at least one is observing the solar photosphere at any time. Synoptic Optical Long-term Investigations of the Sun (SOLIS) at the National Solar Observatory's site on Kitt Peak, Arizona, monitors the vector and longitudinal magnetic fields and the solar chromosphere, and has the ability to observe the disk in a variety of visible spectral wavelengths. It is meant to provide such long-term observations for decades.

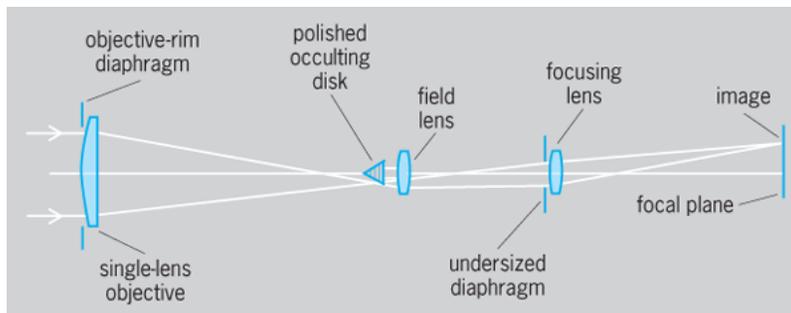


Fig. 23 Optical system of a coronagraph.

Daily images at various wavelengths from the ground and from space are posted at solarmonitor.org. It is hosted by a group at Trinity College, Dublin. *See also:* TELESCOPE.

Coronagraph

Coronagraphs are designed with one overriding consideration: the elimination of instrumental scattered light. Their most delicate task is the observation of a faint source near a bright one. Although originally designed to study the corona immediately adjacent to the disk of the Sun, coronagraphs are also used on stellar telescopes in the search for exoplanets or rings. In an ordinary telescope, dust on the objective, diffraction at the edge of the aperture, and otherwise insignificant defects in the glass of the objective are all sources of diffuse scattered light, which is usually some hundreds of times brighter than the corona. In the Lyot coronagraph (**Fig. 23**), the single-lens objective must be made of flawless glass, which is polished and cleaned to a perfection far beyond average standards. After this, the disk of the Sun is eclipsed by a polished conical disk, and photospheric light diffracted by the rim of the objective is intercepted in its image formed by the field lens, on an undersized diaphragm. The same diaphragm removes double reflection in the primary. The final lens then images the corona on the focal plane. This arrangement reduces scattered light to 10^{-4} of the photosphere. This permits observation of the corona in its emission lines. To observe the continuum (K corona), a polarimeter is needed, as in the Mauna Loa Solar Observatory's Mark IV coronagraph at high altitude on the island of Hawaii. *See also:* POLARIMETRY.

Space platforms have made possible the observation of the corona at great distances from the Sun. The telescope is shielded from the Sun by a series of external occulting disks, each of which removes the diffraction of the preceding one. The C2 and C3 coronagraphs on SOHO and newer coronagraphs on STEREO have facilitated the study of coronal mass ejections. (The C1 coronagraph on SOHO was of a Lyot design, but it suffered from excessive scattered light and, in any case, failed early in the mission.) STEREO's SECCHI package (Sun Earth Connection Coronal and Heliospheric Investigation, with the acronym honoring a nineteenth-century solar physicist) carries an extreme-ultraviolet imager, two coronagraphs (an internally occulted COR1 of the traditional Lyot design for the inner corona, and an externally occulted COR2, for the 2-to-15-solar-radii range), and two

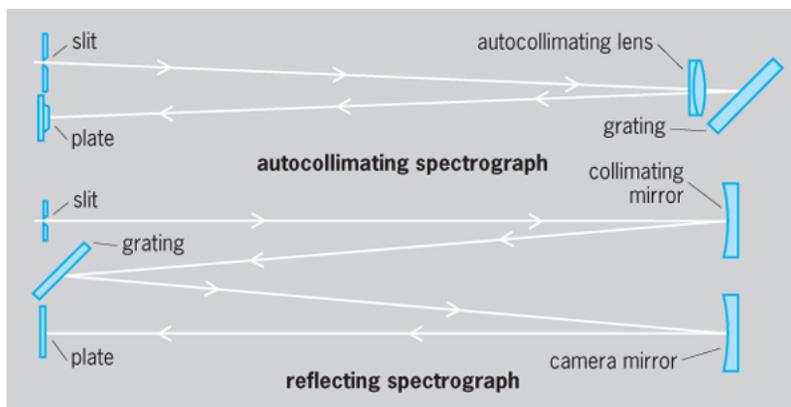


Fig. 24 Two forms of solar spectrograph. Horizontal scale is greatly compressed.

wide-field imagers that look to the side to observe coronal mass ejections as they travel through interplanetary space to Earth.

The coronagraph no longer uniquely provided coronal observations outside of eclipse when coronal observations from spacecraft became possible. Coronagraphs can record the corona only at the limb, whereas soft x-ray and extreme-ultraviolet telescopes reveal the whole corona on the disk. Also, a much greater range of spectral lines is available in the ultraviolet. Thus, only a few coronagraphs remain, but these instruments still have certain capabilities that cannot be matched in space, in particular high spatial resolution and flexibility. They are unexcelled for prominence observation. Since the coronagraphs must be located on mountains, they have limited good seeing since the sites are chosen for low scattering rather than for smooth air.

Spectrographs

Modern solar spectrographs utilize the great brightness of the solar image to achieve dispersion of the order of 100 mm/nm and spectroscopic resolution in excess of 500,000. These desirable characteristics require long focal lengths (10–25 m or 30–80 ft) and superlative diffraction gratings of the largest sizes that remain consistent with accuracy of ruling.

Large solar spectrographs are nearly always either of the Littrow autocollimating type or the reflecting type in which the collimator and camera element are long-focus concave mirrors (**Fig. 24**). They may be mounted either vertically in a well or horizontally on solid concrete piers. The Fourier transform spectrometer has proved extraordinarily powerful because of its high resolution and easy infrared access. *See also:* SPECTROGRAPH; SPECTROSCOPY.

One important use is for magnetic field measurement; circular or linear polarizers are used to isolate the Zeeman components and measure the strength and direction of the magnetic field. It is also possible to produce

monochromatic images by letting the Earth's motion scan the solar image across the slit, recording the spectrum with a CCD, and reconstructing the digital monochromatic images.

Birefringent filter

A much faster route to monochromatic images is afforded by the Lyot birefringent filter. It consists of a multiple sandwich of alternate layers of polarizing films and plates cut from a birefringent crystal (usually quartz or calcite). The assembly transmits the light in a series of sharp, widely spaced wavelength bands. One or another of the polarizers absorbs the light of all intervening wavelengths. A multilayer filter is used to isolate the desired band and exclude the others. An image is obtained of an entire field in the wavelength selected. Filters made for observations on the disk of the Sun generally have transmission bandwidths of 0.025–0.05 nm and can be centered at any visible or near-infrared wavelength. Bandwidths up to 1 nm are used for limb prominences in H α .

By using a switching polarizer, maps of the magnetic field can be made. Successive images in right and left circular polarization in the wing of a line are taken; when these are subtracted, the resulting signal gives the strength and sign of the magnetic field. This device, called the videomagnetograph, is the most sensitive and accurate device for measuring solar magnetic fields. It can also be used for transverse fields. Other kinds of monochromatic filters have been proposed, using Fabry-Perot or Michelson interferometers, but they are generally inferior to the Lyot design. *See also:* BIREFRINGENCE; INTERFEROMETRY; POLARIZED LIGHT.

Interference filters

Techniques developed in recent decades of depositing thin films to provide interference patterns that isolate narrow wavelength regions have led to widespread use of such filters. They are much less expensive than Lyot filters, providing monochromatic imaging on the ground for both professional and amateur astronomers, and are the only possibility for space missions. Their passbands have wings, though, so the images are not as purely monochromatic as they are with Lyot filters or spectroheliographs. The interference patterns are periodic, and therefore require use of auxiliary wider-band blocking filters. *See also:* INTERFERENCE FILTERS.

Space instruments

A range of instruments has been developed for space observations of the Sun in the ultraviolet and x-ray ranges. Light in wavelengths shorter than 125 nm is not reflected by normal mirrors and must be focused by grazing-incidence telescopes. Multilayer coatings provide interference filters that make possible reflection of limited wavelength ranges with normal incidence. For hard x-rays (energies above 30 keV), imaging in this way is not possible, and brute-force imaging with grids is used. A combination of fixed grids gives a Fourier transform of the target image. Such systems are used for flare imaging, where a few extremely bright points are the target. Special detectors are used to give good energy resolution. *See also:* ASTRONOMICAL OBSERVATORY; FOURIER SERIES AND TRANSFORMS; ULTRAVIOLET ASTRONOMY; X-RAY TELESCOPE.

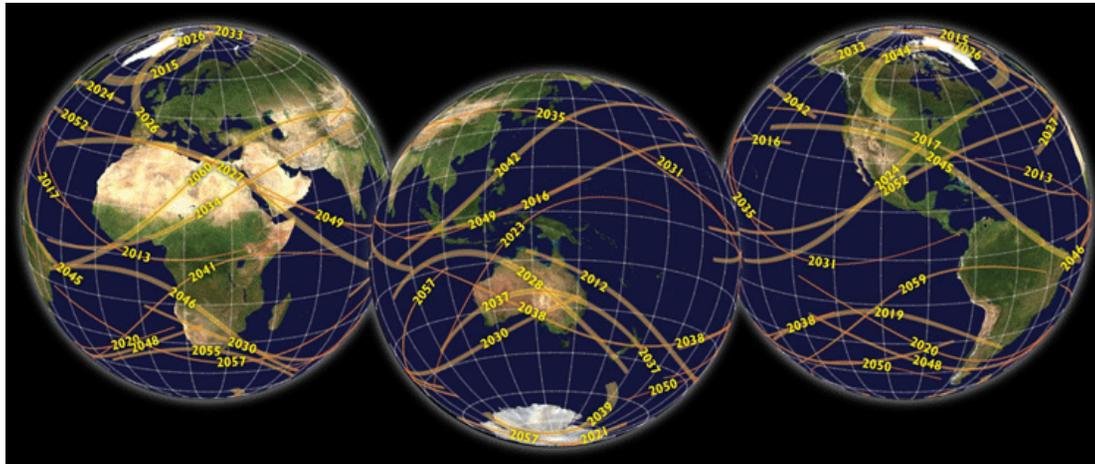


Fig. 25 Total solar eclipses in the period 2010–2060, including some that are hybrid in that the beginnings and ends are annular. (Michael Zeiler, *eclipse-maps.com*, with eclipse paths from Xavier Jubier, *xjubierfree.fr*)

NASA and The Johns Hopkins University Applied Physics Laboratory are developing Solar Probe Plus, for launch in 2018. It is to orbit the Sun 24 times, moving inward during each orbit and eventually penetrating the corona, reaching as close to the Sun as only 7 million km (4 million mi) from the photosphere. Its aims include resolving both the uncertainty of how the corona is heated and the uncertainty of what is accelerating the solar wind. Problems facing Solar Probe Plus include the high temperature to which it will penetrate and the high-velocity dust particles it will encounter. It will carry instruments to measure coronal abundances of the elements, to study the electrons, protons, and helium ions in the solar wind, to image the solar wind, and to measure electric and magnetic fields, radio emissions, and the shock waves that it encounters.

Solar Eclipses

Solar eclipses remain the best way to study certain solar phenomena, since space missions are inflexible in instrumentation once launched and are limited by cost and design to a set of priorities. For example, it remains possible to obtain higher resolution over a wider scale in images of the solar corona at total solar eclipses, to observe in the infrared and other spectral regions not well covered from space, to observe with higher spectral resolution, and to observe with higher time resolution.

Total solar eclipses are visible somewhere on Earth at intervals that average 18 months. Total eclipses include those of 2013 from Africa; 2015 from the Arctic; 2016 from Indonesia; 2017 from the United States; and 2019 from Chile and Argentina (**Fig. 25**).

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