13 The Sun

The Sun is our nearest star. It is important for astronomy because many phenomena which can only be studied indirectly in other stars can be directly observed in the Sun (e.g. stellar rotation, starspots, the structure of the stellar surface). Our present picture of the Sun is based both on observations and on theoretical calculations. Some observations of the Sun disagree with the theoretical solar models. The details of the models will have to be changed, but the general picture should remain valid.

13.1 Internal Structure

The Sun is a typical main sequence star. Its principal properties are:

Mass	$m = M_\odot$	=	1.989×10^{30} kg
Radius	$R = R_\odot$	=	6.960×10^{8} m
Mean density	$\bar{\rho}$	=	1409 kg/m^3
Central density	ρ_c	=	1.6×10^5 kg/m^3
Luminosity	$L = L_\odot$	=	3.9×10^{26} W
Effective temperature	T_e	=	5785 K
Central temperature	T_c	=	1.5×10^7 K
Absolute bolometric magnitude	M_{bol}	=	4.72
Absolute visual magnitude	M_V	=	4.79
Spectral class			G2 V
Colour indices	$B - V$	=	0.62
	$U - B$	=	0.10
Surface chemical composition	X	=	0.71
	Y	=	0.27
	Z	=	0.02
Rotational period			
at the equator			25 d
at latitude 60°			29 d

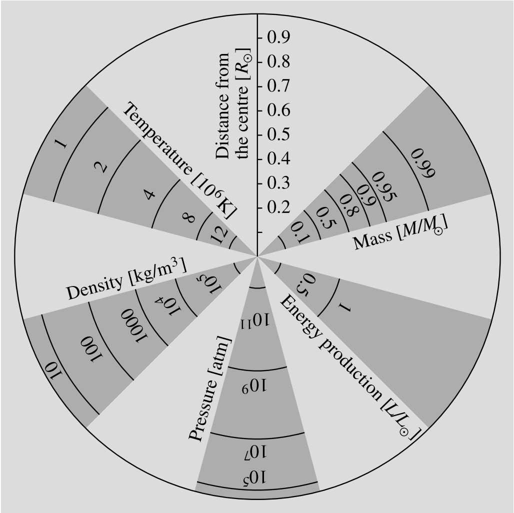

Fig. 13.1 The distribution of temperature, pressure, energy production and mass as functions of radius in the Sun

On the basis of these data, the solar model shown in Fig. 13.1 has been calculated. The energy is produced by the pp chain in a small central region. 99 % of the solar energy is produced within a quarter of the solar radius.

The Sun produces energy at the rate of 4×10^{26} W, which is equivalent to changing about

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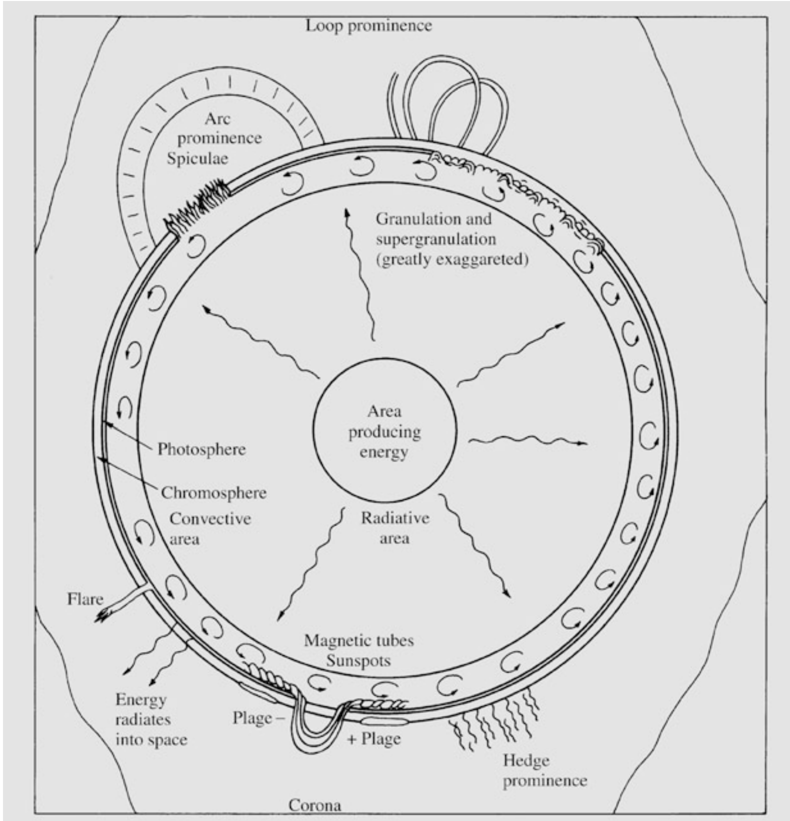

Fig. 13.2 The interior and surface of the Sun. The various kinds of solar phenomena are schematically indicated. (Based on Van Zandt, R.P. (1977): *Astronomy for the Amateur*, Planetary Astronomy, Vol. 1, 3rd edn. (published by the author, Peoria, III.))

four million tonnes of mass into energy every second. The mass of the Sun is so large, about 330,000 times that of the Earth, that during the whole main sequence lifetime of the Sun less than 0.1 % of its mass is turned into energy.

When the Sun formed about 5000 million years ago, its composition was the same everywhere as its present surface composition. Since energy production is concentrated at the very centre, hydrogen is consumed most rapidly there. At about a quarter of the radius the hydrogen abundance is still the same as in the surface layers, but going inwards from that point it rapidly decreases. In the central core only 40 % of the material is hydrogen. About 5 % of the hydrogen in the Sun has been turned into helium.

The radiative central part of the Sun extends to about 70 % of the radius. At that radius the temperature has dropped so much that the gas is no longer completely ionised. The opacity of the solar material then strongly increases, inhibiting the propagation of radiation. In consequence, convection becomes a more efficient means of energy transport. Thus the Sun has a convective envelope (Fig. 13.2).

The Solar Neutrino Problem The central nuclear reactions produce neutrinos at several of the steps in the pp chain (see Fig. 11.5). These neutrinos can propagate freely through the outer layers, and thus give direct information about conditions near the centre of the Sun. When neutrinos from the Sun were first observed in the 1970's, their number was found to be only about a third of what was predicted. This disagreement is called the *solar neutrino problem*.

In the first experiments only neutrinos from the ppII and ppIII branches were observed (Sect. 11.3). Since only a small fraction of the solar luminosity is produced in these reactions, it was not clear what were the consequences of these results for solar models. In the 1990's neutrinos produced in the ppI branch, the main branch of the pp chain, were observed. Although the disagreement with the standard models was slightly smaller in these observations (about 60 % of the predicted flux was observed), the neutrino problem still remained.

Perhaps the most popular explanation for the solar neutrino problem was based on *neutrino oscillations*. According to this explanation, if neutrinos have a small mass (about 10^{-2} eV), an electron neutrino could change into a μ or a τ neutrino as it passed through the outer parts of the Sun. In the early experiments only electron neutrinos were observed, representing only part of the total number of neutrinos produced.

In 2001 the Canadian Sudbury neutrino observatory (SNO) announced results that seemed to solve the problem. The SNO can detect the flux of all different neutrinos and the fraction of the electron neutrinos. The measurements showed that the total neutrino flux was indeed consistent with the predictions of the solar models, but only 35 % of the flux consisted of electron neutrinos. Thus 65 % of the solar electron neutrinos had changed to μ or τ neutrinos while travelling from the Sun to the Earth. Similar observations were also made in a Japanese neutrino observatory. Among the pioneers of the neutrino astronomy are Raymond Davis and Masatoshi Koshiba who shared the Nobel prize in physics in 2002.

The solar neutrino problem can now be considered to be solved. The solution is a great success for the standard solar model. But it has also revealed the existence of neutrino oscillations, proving that neutrinos have a small but non-zero rest mass. This shows that the standard model of particle physics needs to be revised in some respects.

The Solar Rotation As soon as telescopes were introduced, it was observed from the motions of sunspots that the Sun is rotating with a rotational period of about 27 days. As early as 1630 *Christoph Scheiner* showed that there was *differential rotation*: the rotational period near the poles was more than 30 days, while it was only 25 days at the equator. The rotational axis of the Sun is inclined at 7° with respect to the plane of the ecliptic, so that the North Pole of the Sun is best visible from the Earth in September.

The motions of sunspots still give the best information on the rotation near the surface of the Sun. Other surface features also have been used for this purpose. The rotational velocity has also been measured directly from the Doppler effect. The angular velocity is usually written

$$\Omega = A - B \sin^2 \psi, \qquad (13.1)$$

where ψ is the latitude with respect to the equator. The measured values of the coefficients are $A = 14.5$ and $B = 2.9$ degrees/day.

The rotational velocity deeper down in the Sun cannot be directly observed. In the 1980's a method to estimate the rotation in the interior became available, when it became possible to measure the frequencies of solar oscillations from the variations in spectral lines. These oscillations are essentially sound waves produced by turbulent gas motions in the convection zone. These sound waves have calculable oscillation periods (about 3–12 minutes), which depend on the conditions in the solar interior. By comparing the observed and theoretical values one can get information about the conditions deep inside the Sun. The idea of the method is the same as that used when studying the interior of the Earth by means of waves from earthquakes, and it is therefore called *helioseismology*.

Using helioseismology, models for the solar rotation throughout the convection zone have been deduced. It appears that the angular velocity in the whole convection zone is almost the same as at the surface, although it decreases slightly with radius near the equator, and increases near the poles. The angular velocity of the radiative core is still uncertain, but there are indications that the core is rotating as a solid body with approximately the average surface angular velocity. At the bottom of the convection zone there is a thin layer known as the *tachocline*, where the angular velocity changes rapidly with radius. The internal solar rotation according to the helioseismological studies is shown in Fig. 13.3.

The solar differential rotation is maintained by gas motions in the convection zone. Explaining the observed behaviour is a difficult problem that is not yet completely understood.

13.2 The Atmosphere

The solar atmosphere is divided into the *photosphere* and the *chromosphere*. Outside the actual atmosphere, the *corona* extends much further outwards.

The Photosphere The innermost layer of the atmosphere is the photosphere, which is only about 300–500 km thick. The photosphere is the visible surface of the Sun, where the density rapidly increases inwards, hiding the interior from sight. The temperature at the inner boundary of the photosphere is 8000 K and at the outer boundary 4500 K. Near the edge of the solar disk, the line of sight enters the photosphere at a very small angle and never penetrates to large depths. Near the edges one therefore only sees light from the cooler, higher layers. For this reason, the edges appear darker; this phenomenon is known as *limb darkening*. Both the continuous spectrum and the absorption lines are formed in the photosphere, but the light in the absorption lines comes from higher layers and therefore the lines appear dark.

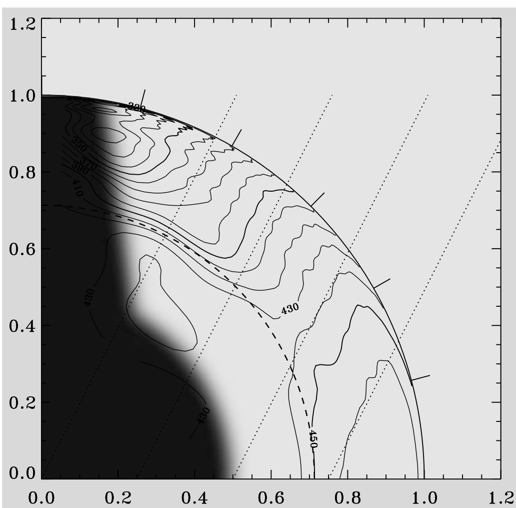

Fig. 13.3 The rotation rate of the Sun inferred from helioseismological observations. The equator is at the horizontal axis and the pole is at the vertical axis, both axes being labelled by fractional radius. Some contours are labelled in nHz, and, for clarity, selected contours are shown as *bold*. (430 nHz is about 26.9 days.) *The dashed circle* is at the base of the convection zone and *the tick marks* at the edge of the outer circle are at latitudes 15°, 30°, 45°, 60°, 75°. *The shaded area* indicates the region in the Sun where no reliable inference can be made with present data. *The slanted dotted lines* are at an angle of 27° with the rotation axis. (Adapted from Schou et al. 1998.) (J. Christensen–Dalsgaard 2007, astro-ph/0610942, Fig. 2)

The solar convection is visible on the surface as the *granulation* (Fig. 13.4), an uneven, constantly changing granular pattern. At the bright centre of each granule, gas is rising upward, and at the darker granule boundaries, it is sinking down again. The size of a granule seen from the Earth is typically 1″, corresponding to about 1000 km on the solar surface. There is also a larger scale convection called *supergranulation* in the photosphere. The cells of the supergranulation may be about 1′ in diameter. The observed velocities in the supergranulation are mainly directed along the solar surface.

The Chromosphere Outside the photosphere there is a layer, perhaps about 500 km thick, where the temperature increases from 4500 K to about 6000 K, the chromosphere. Outside this layer, there is a transition region of a few thousand kilometres, where the chromosphere gradually goes over into the corona. In the outer parts of the transition region, the kinetic temperature is already about 10^6 K.

Normally the chromosphere is not visible, because its radiation is so much weaker than that of the photosphere. However, during total solar eclipses, the chromosphere shines into view for a few seconds at both ends of the total phase, when the Moon hides the photosphere completely. The chromosphere then appears as a thin reddish sickle or ring.

During eclipses the chromospheric spectrum, called the *flash spectrum*, can be observed (Fig. 13.5). It is an emission line spectrum with more than 3000 identified lines. Brightest among these are the lines of hydrogen, helium and certain metals.

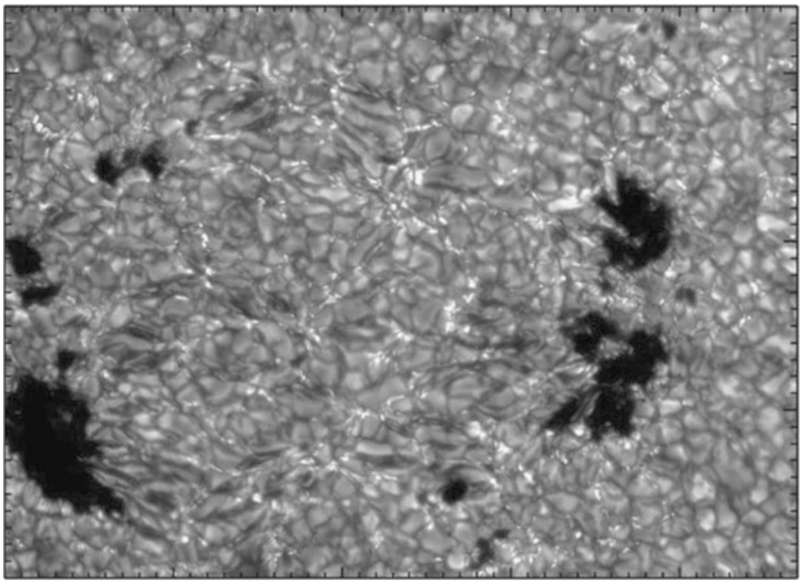

Fig. 13.4 The granulation of the solar surface. The granules are produced by streaming gas. Their typical diameter is 1000 km. The picture was taken in May 13, 2005 with the Swedish one metre solar telescope on La Palma. (Photograph Tom Berger, Royal Swedish Academy of Sciences, ISP/RSAS)

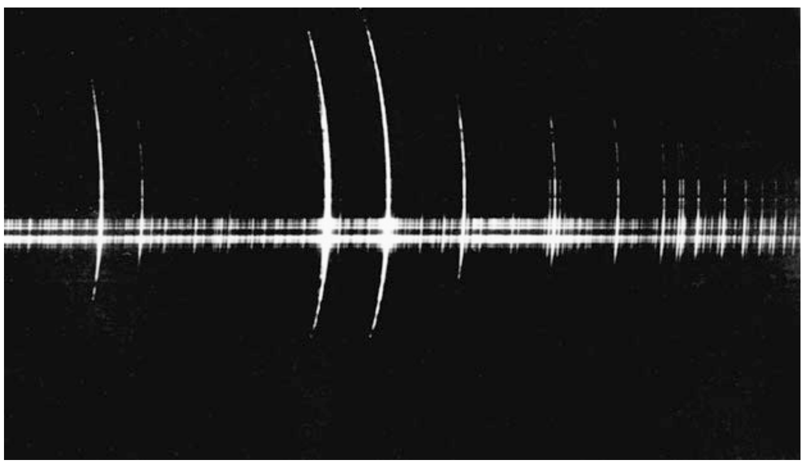

Fig. 13.5 Flash spectrum of the solar chromosphere, showing bright emission lines

One of the strongest chromospheric emission lines is the hydrogen Balmer α line (Fig. 13.6) at a wavelength of 656.3 nm. Since the H_α line in the normal solar spectrum is a very dark absorption line, a photograph taken at this wavelength will show the solar chromosphere. For this purpose, one uses narrow-band filters letting through only the light in the H_α line. The resulting pictures show the solar surface as a mottled, wavy disk. The bright regions are usually the size of a supergranule, and are bounded by *spicules* (Fig. 13.7). These are flamelike structures rising up to 10,000 km above the chromosphere, and lasting for a few minutes. Against the bright surface of the Sun, they look like dark streaks; at the edges, they look like bright flames.

The Corona The chromosphere gradually goes over into the corona. The corona is also best seen during total solar eclipses (Fig. 13.8). It then appears as a halo of light extending out to a few solar radii. The surface brightness of the corona is about that of the full moon, and it is therefore difficult to see next to the bright photosphere.

The inner part of the corona, the K corona, has a continuous spectrum formed by the scattering of the photospheric light by electrons. Fur-

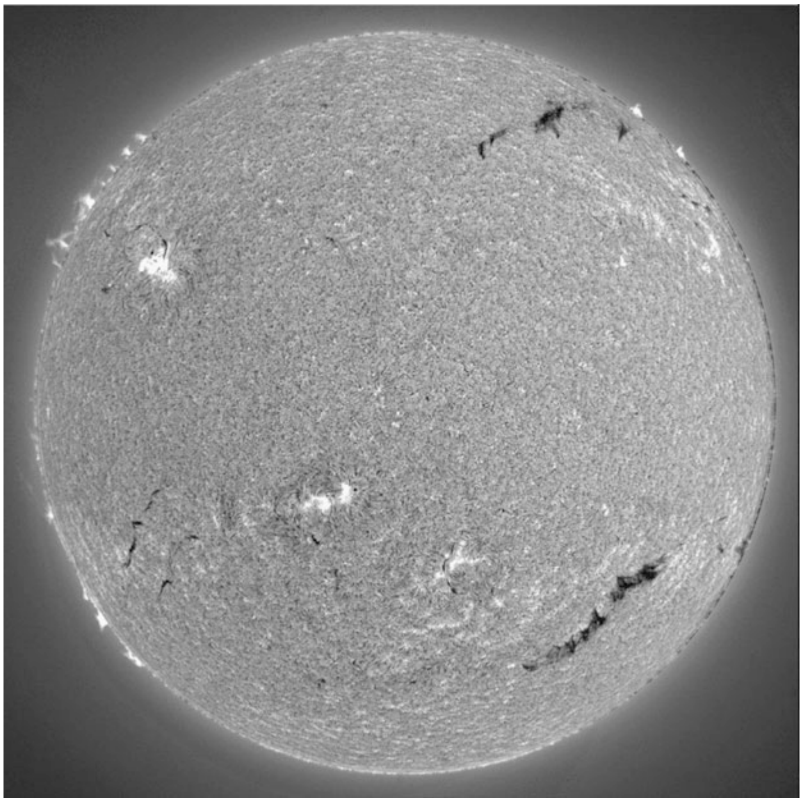

Fig. 13.6 The solar surface in the hydrogen H_α line. Active regions appear bright; the dark filaments are prominences. Limb darkening has been removed artificially, which brings to light spicules and prominences above the limb. The photograph was taken in October 1997. (Photograph Big Bear Solar Observatory/NJIT)

Fig. 13.7 Spicules, flamelike uprisings near the edge of the solar disc. (Photograph Big Bear Solar Observatory)

ther out, a few solar radii from the surface, is the F corona, which has a spectrum showing Fraunhofer absorption lines. The light of the F corona is sunlight scattered by dust.

In the latter part of the 19th century strong emission lines, which did not correspond to those of any known element, were discovered in the corona (Fig. 13.9). It was thought that a new element, called coronium, had been found—a little earlier, helium had been discovered in the Sun before it was known on Earth. About 1940, it was established that the coronal lines were due to highly ionised atoms, e.g. thirteen times ionised iron. Much energy is needed to remove so many

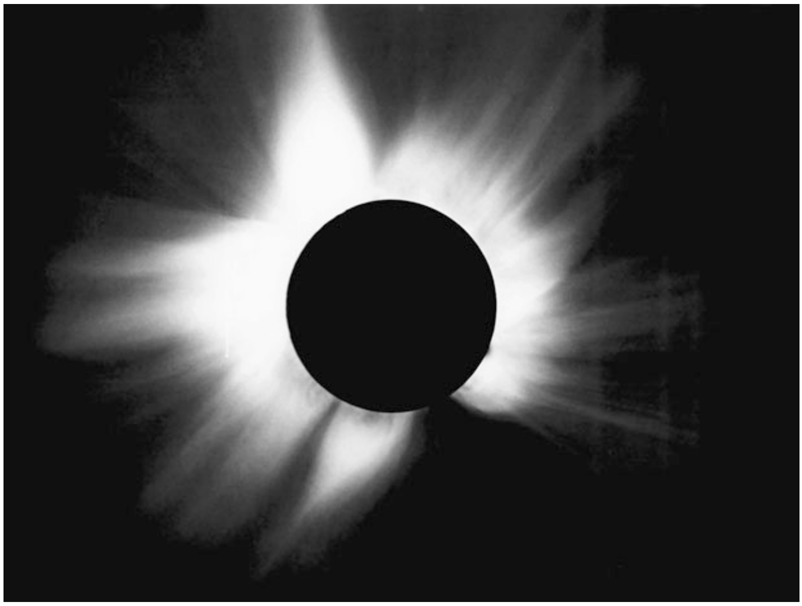

Fig. 13.8 Previously, the corona could be studied only during total solar eclipses. The picture is from the eclipse on March 7, 1970. Nowadays the corona can be studied continuously using a device called the coronagraph

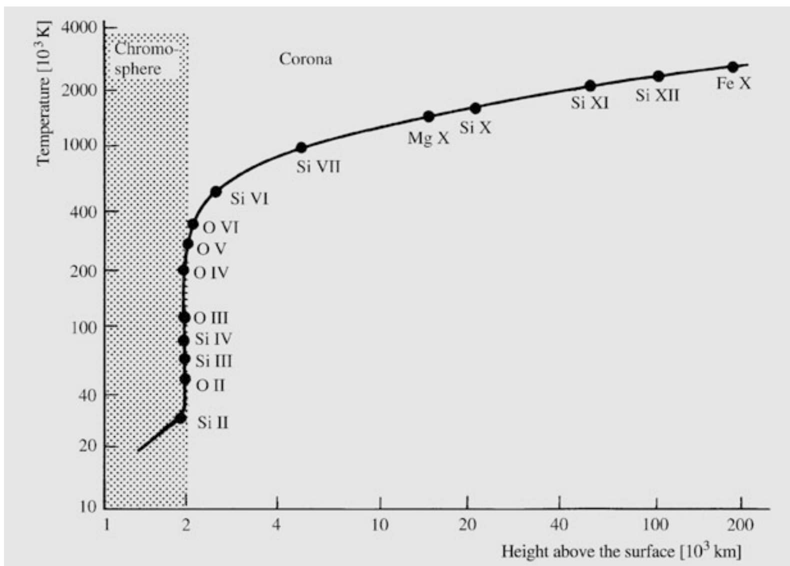

Fig. 13.9 The presence of lines from highly ionised atoms in the coronal spectrum shows that the temperature of the corona has to be very high

electrons from the atoms. The entire corona has to have a temperature of about a million degrees.

A continuous supply of energy is needed in order to maintain the high temperature of the corona. According to earlier theories, the energy came in the form of acoustic or magnetohydrodynamic shock waves generated at the solar surface by the convection. Most recently, heating by electric currents induced by changing magnetic fields has been suggested. Heat would then be generated in the corona almost like in an ordinary light bulb.

In spite of its high temperature the coronal gas is so diffuse that the total energy stored in it is small. It is constantly streaming outwards, gradually becoming a *solar wind*, which carries a flux of particles away from the Sun. The gas lost in

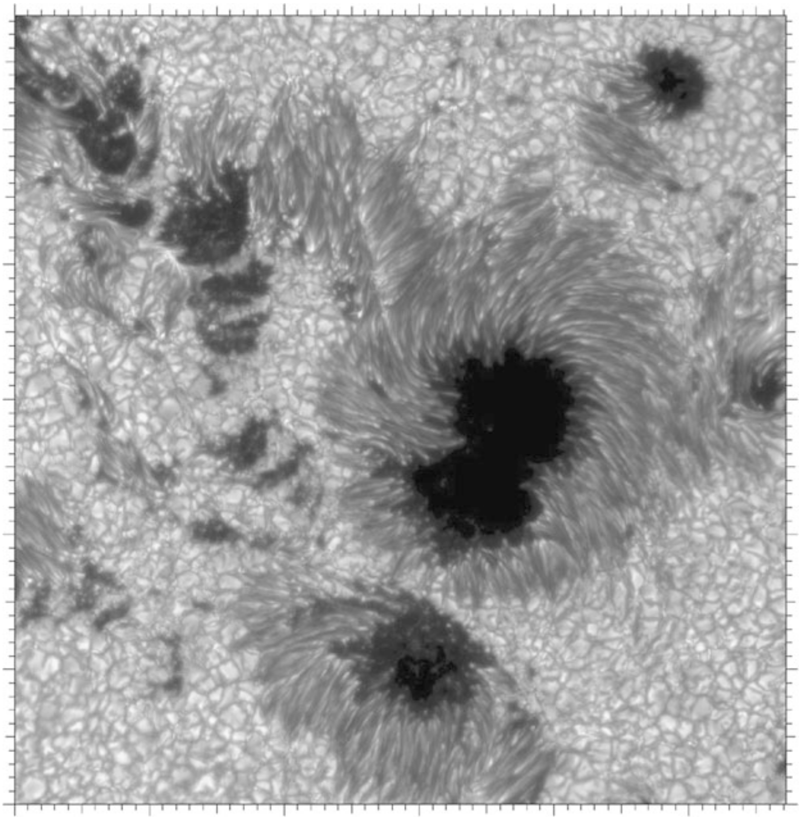

Fig. 13.10 The sunspots are the form of solar activity that has been known for the longest time. The photograph was taken with the Swedish 1-meter Solar Telescope in July 2002. (Photograph Royal Swedish Academy of Sciences)

this way is replaced with new material from the chromosphere.

13.3 Solar Activity

Sunspots The clearest visible sign of solar activity are the *sunspots*. The existence of sunspots has been known for long (Fig. 13.10), since the largest ones can be seen with the naked eye by looking at the Sun through a suitably dense layer of fog. More precise observations became available beginning in the 17th century, when Galilei started to use the telescope for astronomical observations.

A sunspot looks like a ragged hole in the solar surface. In the interior of the spot there is a dark *umbra* and around it, a less dark *penumbra*. By looking at spots near the edge of the solar disk, it can be seen that the spots are slightly depressed with respect to the rest of the surface. The surface temperature in a sunspot is about 1500 K below that of its surroundings, which explains the dark colour of the spots.

The diameter of a typical sunspot is about 10,000 km and its lifetime is from a few days to several months, depending on its size. The larger spots are more likely to be long-lived. Sunspots often occur in pairs or in larger groups. By following the motions of the spots, the period of rotation of the Sun can be determined.

The variations in the number of sunspots have been followed for almost 250 years. The frequency of spots is described by the Zürich sunspot number Z:

$$Z = C(S + 10\,G), \tag{13.2}$$

where S is the number of spots and G the number of spot groups visible at a particular time. C is a constant depending on the observer and the conditions of observation.

In Fig. 13.11, the variations in the Zürich sunspot number between the 18th century and

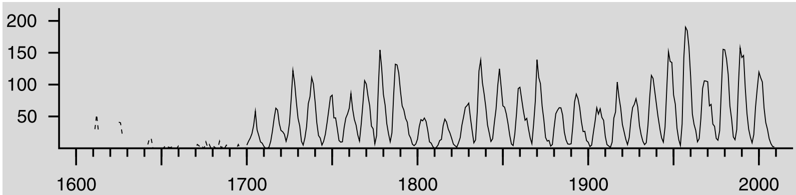

Fig. 13.11 The Zürich sunspot number from 1700 to 2001. Prior to 1700 there are only occasional observations. The number of sunspots and spot groups varies with a period of about 11 years

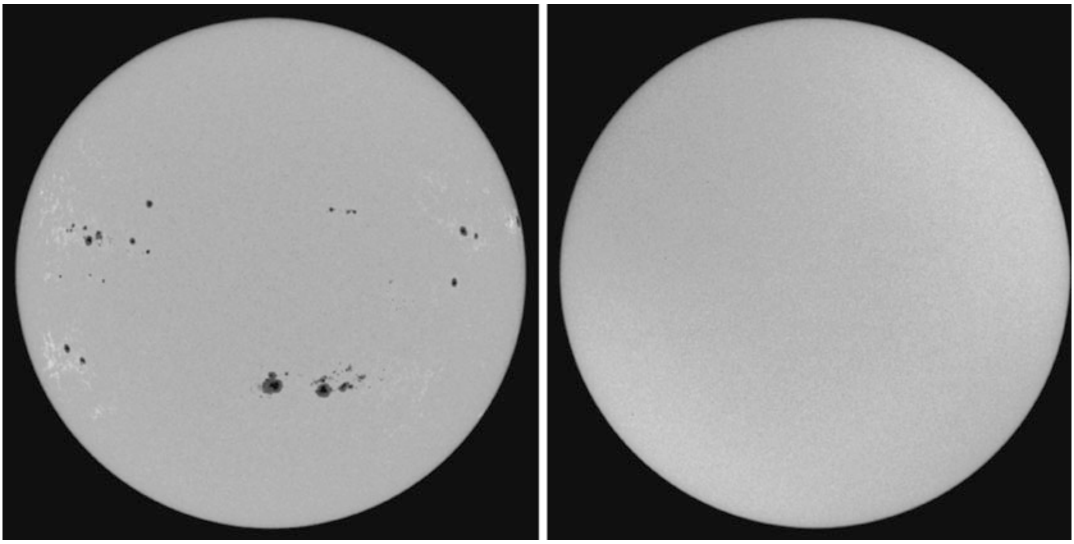

Fig. 13.12 *Left*: During a sunspot maximum (Sept 27, 2001) the Sun is dotted by numerous spots. *Right*: Exactly seven years later no spots are seen, although minimum phase should already be over. (Photos SOHO/MIDI)

the present are shown. Evidently the number of spots varies with an average period of about 11 years. The actual period may be between 7 and 17 years. In the past decades, it has been about 10.5 years. Usually the activity rises to its maximum in about 3–4 years, and then falls off slightly more slowly (Fig. 13.12). The period was first noted by *Samuel Heinrich Schwabe* in 1843.

The variations in the number of sunspots have been fairly regular since the beginning of the 18th century. However, in the 17th century there were long intervals when there were essentially no spots at all. This quiescent period is called the *Maunder minimum*. The similar *Spörer minimum* occurred in the 15th century, and other quiet intervals have been inferred at earlier epochs. The mechanism behind these irregular variations in solar activity is not yet understood.

The magnetic fields in sunspots are measured on the basis of the Zeeman effect, and may be as large as 0.45 tesla. (The magnetic field of the Earth at the equator is 0.03 mT.) The strong magnetic field inhibits convective energy transport, which explains the lower temperature of the spots.

Sunspots often occur in pairs where the components have opposite polarity. The structure of such *bipolar groups* can be understood if the field rises into a loop above the solar surface, connecting the components of the pair. If gas is streaming along such a loop, it becomes visible as a *loop prominence* (Fig. 13.13).

The periodic variation in the number of sunspots reflects a variation in the general solar magnetic field. At the beginning of a new activity cycle spots first begin to appear at latitudes of about

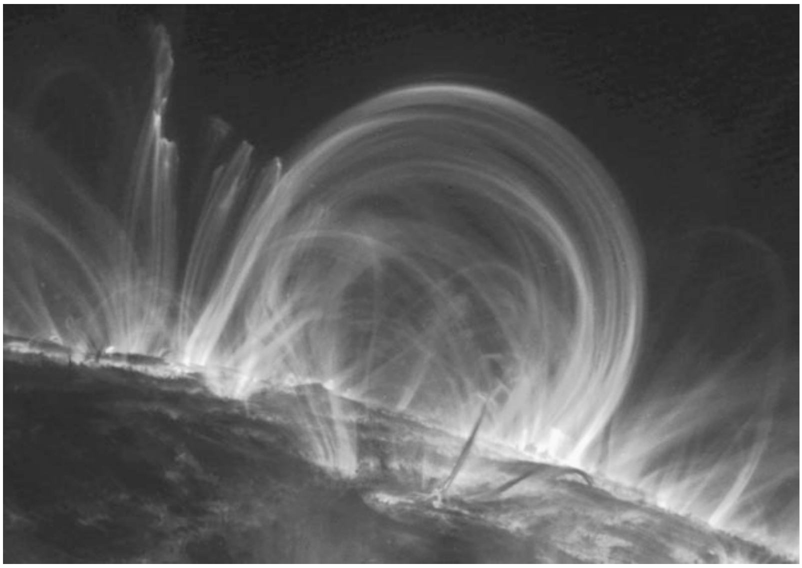

Fig. 13.13 In pairs of sunspots the magnetic field lines form a loop outside the solar surface. Material streaming along the field lines may form loop prominences. Loops of different size can be seen in this image, which the Trace satellite took in 1999. (Photo Trace)

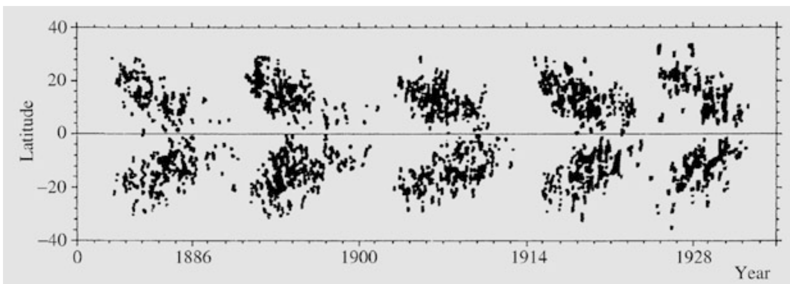

Fig. 13.14 At the beginning of an activity cycle, sunspots appear at high latitudes. As the cycle advances the spots move towards the equator. (Diagram by H. Virtanen, based on Greenwich Observatory observations)

±40°. As the cycle advances, the spots move closer to the equator. The characteristic pattern in which spots appear, shown in Fig. 13.14, is known as the *butterfly diagram*. Spots of the next cycle begin to appear while those of the old one are still present near the equator. Spots belonging to the new cycle have a polarity opposite to that of the old ones. (Spots in opposite hemispheres also have opposite polarity.) Since the field is thus reversed between consecutive 11 year cycles the complete period of solar magnetic activity is 22 years.

The following general qualitative description of the mechanism of the solar cycle was proposed by *Horace W. Babcock*. Starting at a solar minimum, the field will be of a generally dipolar character. Because a conducting medium, such as the outer layers of the Sun, cannot move across the field lines, these will be frozen into the plasma and carried along by it. Thus the differential rotation will draw the field into a tight spiral (Fig. 13.15). In the process the field becomes stronger, and this amplification will be a function of latitude.

When the subsurface field becomes strong enough, it gives rise to a "magnetic buoyancy" that lifts ropes of magnetic flux above the surface. This happens first at a latitude about 40°, and later at lower latitudes. These protruding flux ropes expand into loops forming bipolar groups of spots. As the loops continue expanding they make contact with the general dipolar field, which still remains in the polar regions. This leads to a rapid reconnection of the field lines neutralising the general field. The final result when activity subsides is a dipolar field with a polarity opposite the initial one.

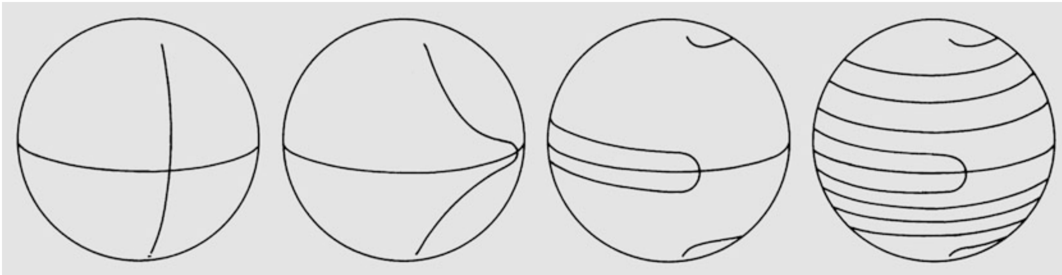

Fig. 13.15 Because the Sun rotates faster at the equator than at the poles, the field lines of the solar magnetic field are drawn out into a tight spiral

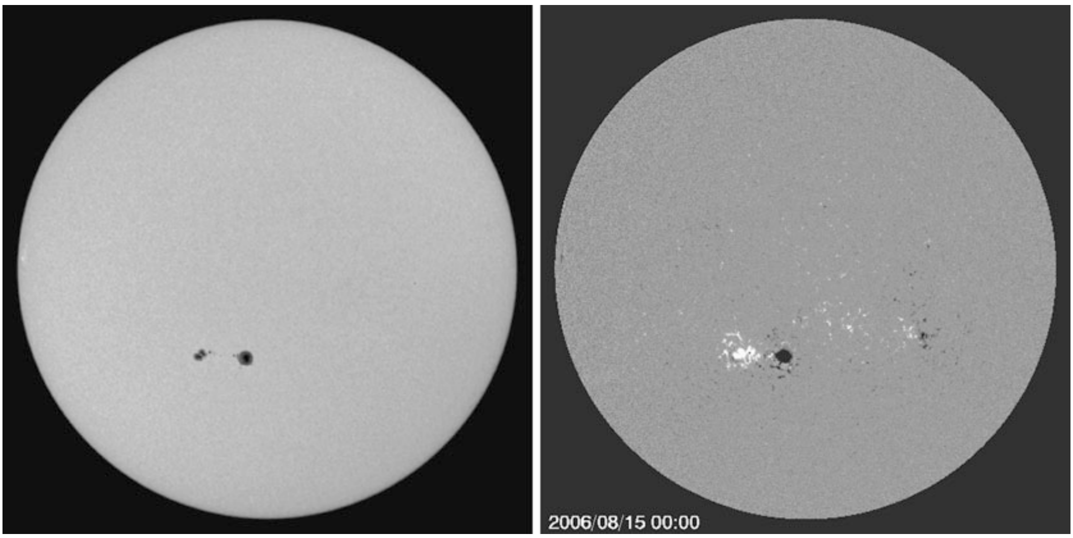

Fig. 13.16 A quiet Sun in August 2006 around the last sunspot minimum. Both pictures were taken by the Michelson Doppler Imager on the SOHO satellite. *On the left* the Sun in visible light, *on the right* a magnetogram, which shows the opposite polarities of the magnetic fields as *black* and *white*. (Photo SOHO/NASA/ESA)

Thus the Babcock model accounts for the butterfly diagram, the formation of bipolar magnetic regions and the general field reversal between activity maxima. Nevertheless, it remains an essentially phenomenological model, and alternative scenarios have been proposed. In *dynamo theory* quantitative models for the origin of magnetic fields in the Sun and other celestial bodies are studied. In these models the field is produced by convection and differential rotation of the gas. A completely satisfactory dynamo model for the solar magnetic cycle has not yet been found. For example, it is not yet known whether the field is produced everywhere in the convection zone, or just in the boundary layer between the convective and radiative regions, as some indications suggest.

Other Activity The Sun shows several other types of surface activity: *faculae* and *plages*; *prominences*; *flares*.

The faculae and plages are local bright regions in the photosphere and chromosphere, respectively. Observations of the plages are made in the hydrogen H_α or the calcium K lines (Fig. 13.16). The plages usually occur where new sunspots are forming, and disappear when the spots disappear. Apparently they are caused by the enhanced heating of the chromosphere in strong magnetic fields.

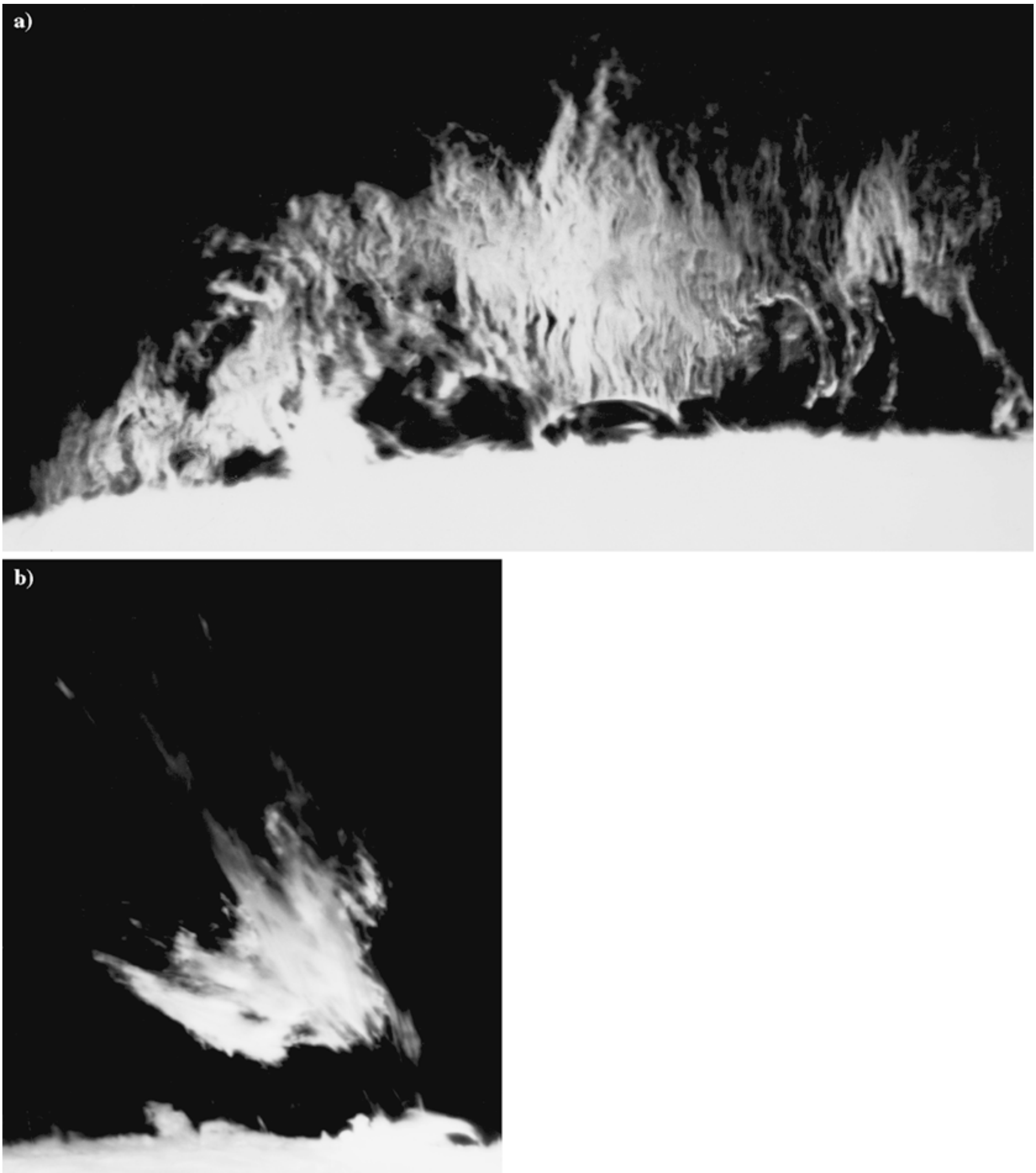

Fig. 13.17 (**a**) Quiescent "hedgerow" prominence. (Photograph Sacramento Peak Observatory.) (**b**) Larger eruptive prominence. (Photograph Big Bear Solar Observatory)

The prominences are among the most spectacular solar phenomena. They are glowing gas masses in the corona, easily observed near the edge of the Sun. There are several types of prominences (Fig. 13.17): the quiescent prominences, where the gas is slowly sinking along the magnetic field lines; loop prominences, connected with magnetic field loops in sunspots; and the rarer eruptive prominences, where gas is violently thrown outwards.

The temperature of prominences is about 10,000–20,000 K. In H_α photographs of the chromosphere, the prominences appear as dark filaments against the solar surface (Fig. 13.6).

The flare outbursts are among the most violent forms of solar activity (Fig. 13.18). They appear

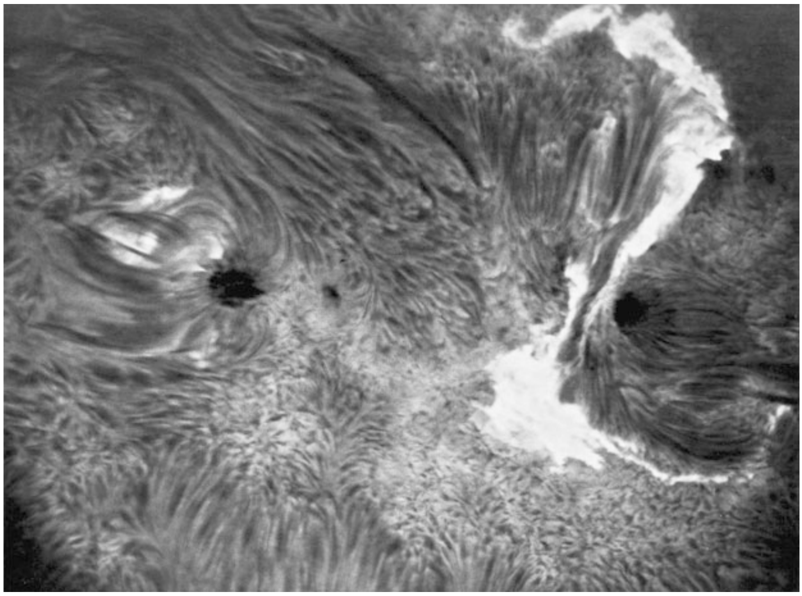

Fig. 13.18 A violent flare near some small sunspots. (Photograph Sacramento Peak Observatory)

as bright flashes, lasting from one second to just under an hour. In the flares a large amount of energy stored in the magnetic field is suddenly released. The detailed mechanism is not yet known.

Flares can be observed at all wavelengths. The hard X-ray emission of the Sun may increase hundredfold during a flare. Several different types of flares are observed at radio wavelengths. The emission of solar cosmic ray particles also rises.

Prominences and flares are often accompanied with *coronal mass ejections* Fast moving (500–2000 km/s) clouds cause shock waves accelerating particles to very high velocities. Particles in flares are the fastest ($v \approx 0.3c$). Particles in a magnetic cloud travelling at the velocity of the mass ejection reach the Earth in a couple of days. Particles activated by the shock wave arrive continuously affecting the space weather and causing magnetic storms.

The flares and coronal mass ejections give rise to disturbances on the Earth. The X-rays cause changes in the ionosphere, which affect short-wave radio communications. The particles give rise to strong auroras when they enter the Earth's magnetic field a few days after the outburst.

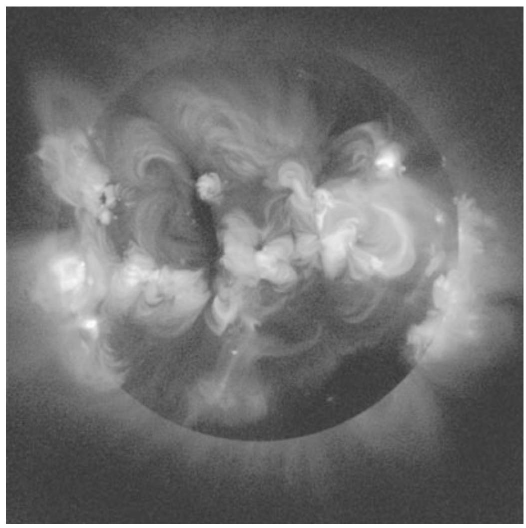

Fig. 13.19 An X-ray picture of the active Sun, taken by the Japanese Yohkoh satellite in 1999, around the last maximum of sunspot activity. (Photo JAXA)

Solar Radio Emission The Sun is the strongest radio source in the sky and has been observed since the 1940's. In contrast to optical emission the radio picture of the Sun shows a strong *limb brightening*. This is because the radio radiation comes from the upper layers of the atmosphere. Since the propagation of radio waves is obstructed by free electrons, the high electron density near the surface prevents radio radiation from getting out. Shorter wavelengths can propa-

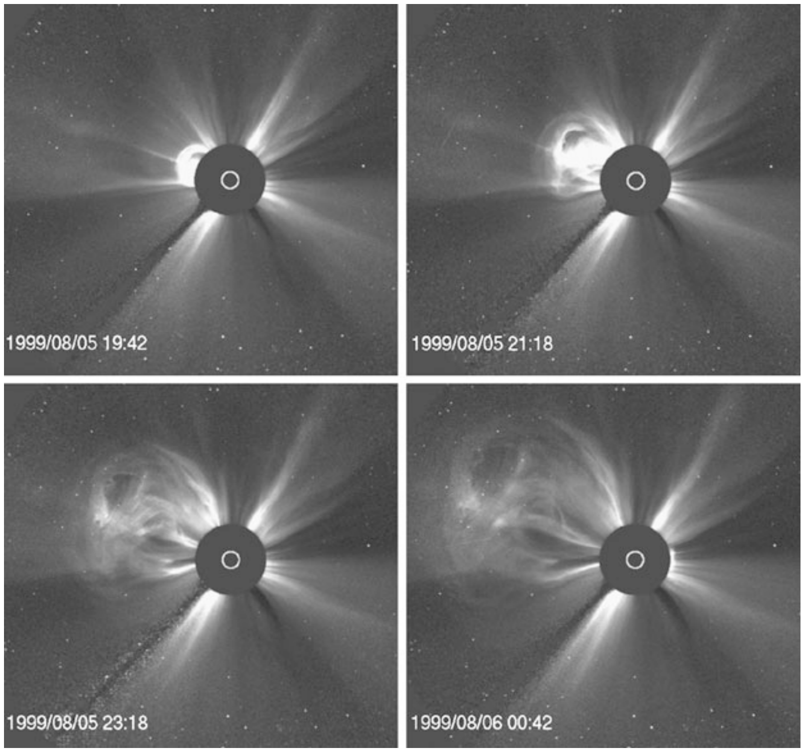

Fig. 13.20 The SOHO (Solar and Heliospheric Observatory) satellite keeps a constant watch on the Sun and its surroundings in many wavelengths. Here the LASCO (Large Angle and Spectrometric Coronagraph) instrument sees a large Coronal Mass Ejection erupting from the Sun. The surface of the Sun is covered by a disk, and the size and position of the Sun is indicated by the white circle. (Photo SOHO/NASA/ESA)

gate more easily, and thus millimetre-wavelength observations give a picture of deeper layers in the atmosphere, whereas the long wavelengths show the upper layers. (The 10 cm emission originates in the upper layers of the chromosphere and the 1 m emission, in the corona.)

The Sun looks different at different wavelengths. At long wavelengths the radiation is coming from the largest area, and its electron temperature is about 10^6 K, since it originates in the corona.

The radio emission of the Sun is constantly changing according to solar activity. During large storms the total emission may be 100,000 times higher than normal. Especially the motion of shock waves can be followed by the radio emission, since the electrons accelerated by the shock generate radio emission (type II radio bursts).

X-ray and UV Radiation The X-ray emission of the Sun is also related to active regions (Fig. 13.19). Signs of activity are bright *X-ray regions* and smaller *X-ray bright points*, which last for around ten hours. The inner solar corona also emits X-rays. Near the solar poles there are *coronal holes*, where the X-ray emission is weak.

Ultraviolet pictures of the solar surface show it as much more irregular than it appears in visible light. Most of the surface does not emit much UV radiation, but there are large active regions that are very bright in the ultraviolet.

Several satellites have made observations of the Sun at UV and X-ray wavelengths, for example Soho (Solar and Heliospheric Observatory, 1995–, Fig. 13.20). These observations have made possible detailed studies of the outer layers of the Sun. Observations of other stars have revealed coronae, chromospheres and magnetic variations similar to those in the Sun. Thus the new observational techniques have brought the physics of the Sun and the stars nearer to each other.

13.4 Solar Wind and Space Weather

A continuous stream of charged particles is coming from the Sun as the solar wind, varying with the solar activity. The coronal mass ejections are considered as “disturbances”. Around a minimum mass ejections may occur a few times a week; around a maximum there may be several ejections every day. The solar wind consists mainly of electrons and protons. At the distance of the Earth there are typically 5–10 particles per cubic centimetre. There are also some nuclei of helium atoms. The velocity is the solar wind close to the poles of the Sun is about 800 km/s but around the equator only about 300 km/s. At the distance of the Earth the velocity of the particles is about 500 km/s on the average. The Sun loses $2 - 3 \times 10^{-14} M_\odot$ of its mass every year as solar wind.

Magnetic fields of planets direct the motions of the particles of the solar wind (Sect. 7.7). The auroras are the most outstanding phenomenon on the Earth. Currents induced by the charged particles can also have considerable negative effects. They can damage satellites and even electric networks. The most serious accident this far happened in 1989 in Quebec when a high voltage network was damaged and millions of people had to survive without electricity for several hours.

Space weather mean the interaction of the solar wind and the magnetic environment of the Earth. Because of its effects it is now followed actively. The space weather affects the upper atmosphere but it is still debated whether it is connected to variations of the weather and climate.

13.5 Example

Example 13.1 Assume that the Sun converts 0.8 % of its mass into energy. Find an upper limit for the age of the Sun, assuming that its luminosity has remained constant.

The total amount of energy released is

$$\begin{aligned} E &= mc^2 = 0.008\, M_\odot c^2 \\ &= 0.008 \times 2 \times 10^{30}\ \mathrm{kg} \times \left(3 \times 10^{8}\ \mathrm{m\,s^{-1}}\right)^2 \\ &= 1.4 \times 10^{45}\ \mathrm{J}. \end{aligned}$$

The time needed to radiate this energy is

$$\begin{aligned} t &= \frac{E}{L_\odot} = \frac{1.4 \times 10^{45}\ \mathrm{J}}{3.9 \times 10^{26}\ \mathrm{W}} \\ &= 3.6 \times 10^{18}\ \mathrm{s} \approx 10^{11}\ \text{years}. \end{aligned}$$

13.6 Exercises

Exercise 13.1 The solar constant, i.e. the flux density of the solar radiation at the distance of the Earth is $1370\ \mathrm{W\,m^{-2}}$.

(a) Find the flux density on the surface of the Sun, when the apparent diameter of the Sun is $32'$.
(b) How many square metres of solar surface is needed to produce 1000 megawatts?

Exercise 13.2 Some theories have assumed that the effective temperature of the Sun 4.5 billion years ago was 5000 K and radius 1.02 times the current radius. What was the solar constant then? Assume that the orbit of the Earth has not changed.