Astrophysics and Space Science Library 471

Boris Filippov

Eruptions on the Sun

Springer

Astrophysics and Space Science Library

Volume 471

The Astrophysics and Space Science Library is a series of high-level monographs and edited volumes covering a broad range of subjects in Astrophysics, Astronomy, Cosmology, and Space Science. The authors are distinguished specialists with international reputations in their fields of expertise. Each title is carefully supervised and aims to provide an in-depth understanding by offering detailed background and the results of state-of-the-art research. The subjects are placed in the broader context of related disciplines such as Engineering, Computer Science, Environmental Science, and Nuclear and Particle Physics. The ASSL series offers a reliable resource for scientific professional researchers and advanced graduate students.

Boris Filippov

Eruptions on the Sun

Springer

Boris Filippov
Department of Solar Physics and Solar-Terrrestrial Relations
Pushkov Institute of Terrestrial
Magnetism, Ionosphere and Radio Wave
Rropagation, Russian Academy of
Sciences (IZMIRAN)
Moscow, Troitsk, Russia

ISSN 0067-0057 ISSN 2214-7985 (electronic)
Astrophysics and Space Science Library
ISBN 978-3-031-58176-2 ISBN 978-3-031-58177-9 (eBook)
https://doi.org/10.1007/978-3-031-58177-9

Collage showing the propagation of a Coronal Mass Ejection from the Sun to the Earth's magnetosphere. Credit: The Author

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This book is devoted to eruptive phenomena on the Sun, the most dangerous sources of space weather disturbances. It discusses the latest achievements in this field, described in the scientific literature and obtained by the author himself.

The initial chapters of the book give a brief description of the role of the Sun in the life and history of mankind, a general description of the solar interior and the atmosphere of the Sun, the causes and drivers of solar activity and its impact on the Earth's environment and human life.

The book provides a detailed description of eruptive phenomena on the Sun, a review of observations of solar activity and theoretical ideas about the mechanisms and causes of a sudden release of energy in the solar atmosphere. Much attention is paid to the solar magnetic fields, their characteristic features and measured values in the photosphere, the observed manifestations in the chromosphere and corona, and methods for extrapolating photospheric data to the upper layers of the solar atmosphere. It is assumed that the magnetic field is the source of energy suddenly released during eruptive phenomena observed in the form of flares, prominence eruptions, and coronal mass ejections (CMEs). Energy is accumulated and stored in the non-potential (associated with electric currents) part of the coronal magnetic field (free magnetic energy). This part of the field is the most variable and can provide energy for fast eruptive processes. CMEs, propagating through the interplanetary medium, significantly perturb it and cause the strongest geomagnetic storms when they affect the Earth's magnetosphere. The prediction of the arrival of a CME is the key problem of the entire space weather forecast. Thus, pre-eruptive conditions in CME source regions are of great importance. Solar prominences and filaments are considered the most likely progenitors of CMEs. Most of the book is devoted to the description and analysis of their equilibrium and stability. It is shown that there are measurable characteristics of the proximity of a prominence to the instability threshold, which can be very useful in the problem of space weather forecasting.

The book contains many illustrations and links to the latest scientific articles and reviews on the topic. I hope it will be useful to researchers in the field of astrophysics, solar physics, geophysics, as well as PhD and graduate students.

Troitsk, Russia Boris Filippov

Contents

Chapter 1
Introduction

For the inhabitants of the Earth, the Sun is the main source of heat and light. Thanks to its stability, living conditions on the Earth remain unchanged, at least on time scales smaller than geological ones. Our Sun is just one of the countless stars that dot the black sky on a moonless night (Fig. 1.1). The uniqueness of this star is that it is "ours" and is located very close by astronomical standards, 150 million kilometers away. The closest neighbor of the Sun in the stellar world, Proxima Centauri, is 300 thousand times further away. Fortunately for us, the Sun is a fairly "peaceful" star. It shines and shines unchanged for billions of years. In fact, not all stars are like this. There are variable and non-stationary stars, the radiation of which changes before our eyes. For the energy radiated by the Sun, they even came up with a special term, the solar constant, reflecting its immutability. (Modern more accurate measurements in outer space during the space age have shown that there are indeed very small changes in energy flow, less than 1%. For this reason, the term "solar constant" has been replaced by the term "*Total Solar Irradiance*" (TSI). For every square meter of the Earth's surface (more precisely, the area in the Earth's orbit, perpendicular to the Sun's rays) there is 1.35 kW of solar energy. No wonder it's so hot under the sun at its zenith: every square meter has a good electric stove. Seasonal weather changes are not associated with the variability of the flow of energy coming from the Sun, but with changes in its height above the horizon due to the inclination of the Earth's rotation axis to the plane of the Earth's orbit (ecliptic) by 23.5°.

But it is not for nothing that they say that there are devils in stagnant waters. There is something about the seemingly calm Sun. Firstly, it has long been known that dark spots appear on the surface of the solar disk. We will discuss what these sunspots are a little later. Secondly, when people learned to "see" not only in the usual range of electromagnetic waves, represented by the colors of the rainbow, but also (with the help of instruments) in the radio range, as well as in the ultraviolet and X-ray parts of the spectrum (the latter only after breaking through into space beyond the atmosphere that absorbs this radiation) it turned out that the Sun changes its brightness in some wavelengths by tens and hundreds of times. This inconstancy and windiness was called *solar activity*. As it turned out, partly it is predictable, and partly not, at

B. Filippov, *Eruptions on the Sun*, Astrophysics and Space Science Library 471,
https://doi.org/10.1007/978-3-031-58177-9_1

Fig. 1.1 Spiral galaxy Messier 101 (M101, also known as NGC 5457 and also nicknamed the Pinwheel Galaxy). Image taken with the Hubble Space Telescope. in the Canary Islands (taken from http://www.seds.org). It looks similar to our Galaxy (the Milky Way) observed from a direction perpendicular to the plane of the galactic disk. Our Sun is located near the equatorial plane of symmetry of the disk at a distance of about 0.6 radius of the galaxy from its center. The estimated position of the Sun is shown with its greatly enlarged image. (Credit: ESA/Hubble and NASA/SDO/AIA. (https://en.wikipedia.org/wiki/File:M101_hires_STScI-PRC2006-10a.jpg))

least these days. Solar activity owes its existence to the presence of fairly strong *magnetic fields* on the Sun. The Sun would be a rather boring object to study if it did not have a magnetic field. Unlike the Earth's magnetic field, which is regular and constant enough to be used for navigation, the Sun's magnetic field has a complex structure and changes according to complex laws. The interaction of highly conductive plasma, in which movements such as rotation, global circulation, convection, and turbulence occur, with the magnetic field, gives rise to many specific manifestations of solar activity. On the time scale of development of these processes, two characteristic scales can be distinguished. The first, measured in years and decades, characterizes the general evolution and distribution of the field on the surface of the Sun. The second scale, minutes or hours, is associated with a sudden sporadic release of energy in the solar atmosphere as a result of rapid non-stationary processes of magnetic field restructuring.

The variability of the Sun associated with its magnetic activity affects the Earth's processes. Although sunspots during the maximum activity can occupy up to 1% of the visible hemisphere, the decrease in radiation flux in them is usually more than compensated by an increase in the radiation flux in the *plages* accompanying the sunspots. As a result, during the years of maximum activity, the integral radiation flux (TSI) slightly increases (on average, no more than 0.1%). It is difficult to judge whether these small cyclic changes in the energy flow affect the Earth's climate, since other solar active processes influencing the Earth also act synchronously with them. One of the constantly acting, but experiencing significant variations, influencing agents is the *solar wind*. A plasma stream with a frozen-in magnetic field crashes into the Earth's magnetosphere, compresses it from the front side, and extends a long tail from the night side. Changing wind parameters changes the state of the magnetosphere, induces electric currents, initiates magnetic energy conversion processes similar to solar flares, and causes precipitation of particles from radiation belts. Geomagnetic storms are recorded on the Earth's surface, and auroras are observed at high latitudes. Even the stationary solar wind is very inhomogeneous in angular space, since it originates in regions of the corona with different magnetic topologies. Fast solar wind comes from regions with open field lines, coronal holes. Slow wind originates in areas with a closed magnetic configuration. The onset of a geomagnetic storm is often associated with the arrival of high-speed solar plasma. Particularly favorable conditions for the development of a storm are formed when the plasma carries a magnetic field with a component directed opposite to the Earth's magnetic field. Due to the rotation of the Sun and the movement of the Earth in its orbit, we enter a stream with the same characteristics after about 27 days, so geomagnetic disturbances tend to recur with this period.

In addition to the stationary solar wind, there are disturbances in the interplanetary medium associated with non-stationary processes in the solar atmosphere. 8 min after the flare, its X-ray and ultraviolet radiation, reaching the Earth's atmosphere, causes additional ionization in the ionosphere, especially in its lower D layer, which causes increased attenuation of short-wave radio waves and disruption of radio communications. Ultraviolet and X-ray radiation heats up the upper atmosphere layers, increasing the altitude scale. As a result, the density of the atmosphere at the heights of low-orbiting satellites increases, significantly increasing their drag and deceleration, which leads to changes in orbits and premature re-entry down to Earth. Following the electromagnetic radiation of the flare, energetic particles, solar cosmic rays, arrive with a delay of 10–30 min to several hours. They create a radiation hazard for the crews of orbital stations and high-altitude aircraft in polar latitudes. Satellite electronics are also under threat. 1–4 days after the event on the Sun, accompanied by a *coronal mass ejection* (CME) in the direction towards the Earth, a plasma cloud with a frozen-in magnetic field and an excited shock wave reaches the vicinity of the Earth. Its collision with the magnetosphere leads to the development of a *geomagnetic storm*, which causes many effects, mostly negative. In long power lines, variations in the Earth's magnetic field induce additional electric direct currents that can damage electrical equipment; the same currents in oil and gas pipelines cause increased corrosion of metals, leading to premature wear of pipes. Disturbances of the geomagnetic field undoubtedly affect biological objects, in particular, the well-being of people suffering from cardiovascular and some other diseases.

There is another not quite direct mechanism of the impact of solar activity on the Earth's climate. During the epoch of maximum, the magnetic field has a more

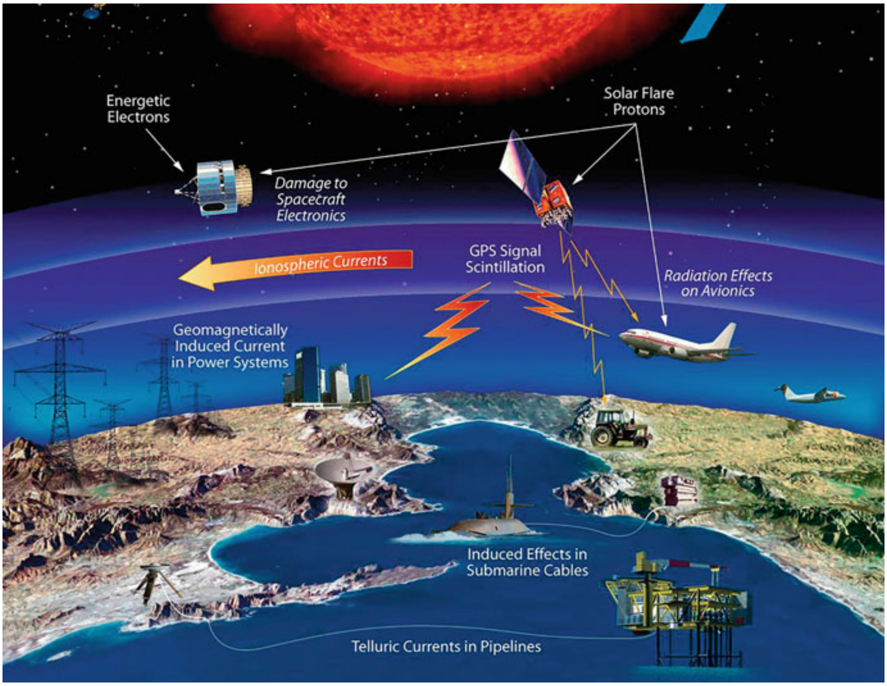

Fig. 1.2 Effect of space weather events on technological and infrastructural systems. (Credit: NASA)

complex and intricate structure not only near the surface of the Sun, but throughout the entire heliosphere. Such a field strongly scatters galactic cosmic rays, weakening their flux near the Earth. According to a number of experts, high-energy particles of galactic cosmic rays, capable of penetrating deep enough into the atmosphere, ionizing many atmospheric atoms, create condensation centers that initiate the formation of clouds. Thus, cloudiness, which reflects part of the solar energy, should increase during the years of minimum activity, which will lead to a decrease in the average temperature at the Earth's surface. For example, a significant cooling in Europe in the seventeenth century might be associated with the almost complete absence of sunspots on the Sun for seven decades (the so-called Maunder minimum).

The variability of the parameters of the interplanetary medium in the vicinity of the Earth, affecting the state of the magnetosphere and a number of aspects of the life of modern civilization, gave rise to the term "*space weather*" (Fig. 1.2), which reflects the state of the electromagnetic environment in near-Earth space, the levels of various radiation fluxes, energetic particles, etc. The "kitchen" of the formation of this weather is the Sun, its activity, and non-stationary processes in its atmosphere. Let's start from a brief overview of the general characteristics of the Sun and its activity.

Chapter 2
General Characteristics of the Sun

2.1 The Sun as a Star

The Sun is the central body of the solar system, a dwarf star of spectral type G2V. The Sun is located at the edge of one of the spiral arms of our Galaxy at a distance of about 10 kiloparsecs from its center (Fig. 1.1). Although the Sun is a fairly typical star, it has not yet been possible to find its "twin"—a star with exactly the same parameters and properties. The most likely candidate for the "celestial twins" of the Sun is the star number 18 in the constellation Scorpius, located at a distance of 46 light years (Porto de Mello et al., 2014). At the same time, the Sun, of course, is unique not only because it is its energy that ensures the existence of life on the Earth, but also because it is the only star whose surface details are well resolved and accessible for detailed study. The relative proximity makes it possible now to discuss the acquisition of data not only by remote, astronomical methods, but also measurements directly close to the object itself *in situ*. Space observatories register particle fluxes emitted by the Sun, fields generated by it in various parts of the Solar System. The *Helios* spacecraft (Porsche, 1977) approached the Sun at a distance of 60 solar radii $R_\odot$ (three and a half times closer than the Earth). The *Ulysses* probe (Wenzel et al., 1992), for the first time, went far from the ecliptic plane and flew over the polar regions of the Sun at a distance of 2 AU. *Solar Orbiter* (Müller et al., 2013; https://www.nasa.gov/content/solar-orbiter-overview) is a mission preparing to approach along a spiral trajectory up to ~60 $R_\odot$ and to raise the orbital inclination to about 24°. *Parker Solar Probe* (Nisticò et al., 2019; https://www.nasa.gov/content/goddard/parker-solar-probe) will fly through the Sun's atmosphere at a distance of about ten radii from the solar surface.

Nevertheless, the main channel of information about the Sun is its electromagnetic radiation in various wave bands, recorded on the Earth's surface or in space. The maximum in the spectral distribution of continuous electromagnetic radiation falls on the region of visible light ~4600 Å, which corresponds to the radiation of a completely black body with a temperature of about 6000 K. Most of the visible light

B. Filippov, *Eruptions on the Sun*, Astrophysics and Space Science Library 471,
https://doi.org/10.1007/978-3-031-58177-9_2

comes from a layer that is very thin for the scale of the Sun, only about 300 km thick, called the *photosphere*. Thanks to this, we see a very sharp edge of the Sun, despite the fact that, like any star, it is a gas ball in which the density decreases according to the barometric law. Photons re-emitted by the photosphere no longer carry information about matter in deeper layers, and until recently we knew no more about the internal structure of the Sun than about the interiors of other stars. Our knowledge was based only on modeling, the correctness of which was checked by the most general characteristics of the star, such as mass, size, luminosity, and spectral type.

Only in the last two decades, astrophysicists have learned to receive information from agents that have a greater penetrating power than electromagnetic waves. These are acoustic waves and neutrinos. In the early 1960s, fluctuations in the surface of the Sun with a period of 3–10 min, the so-called 5-min fluctuations, were discovered. The oscillation amplitude is small, the velocities are within 100 m s^{-1}, but they are remarkable for their constancy and generality. These oscillations are a manifestation of the "ringing" of the solar ball as an acoustic resonator. Acoustic waves propagating inside the Sun are reflected from the region of a sharp drop in density at the boundary of the photosphere. Inside the Sun, the waves undergo refraction and again head towards the surface, thus circling the entire sphere. If an integer number of such dips fits on the circumference of the Sun, then the wave of the given frequency is amplified. Therefore, an analysis of the frequencies of the observed oscillations provides information about the parameters of the plasma in the inner parts of the Sun. This line of research is called *helioseismology*.

Another agent capable of escaping from the deepest interior of the Sun is the *neutrino*. These particles interact so weakly with matter that they freely pass through the entire thickness of the Sun from the zone of thermonuclear reactions of fusion in the central part (the core of the Sun). The difficulty lies in how to register them on the Earth. Although neutrino detectors turned out to be somewhat cumbersome (in them, single atoms are released from hundreds of tons of target matter, which are products of the reaction of nuclei with neutrinos), they began to confidently measure the neutrino flux from the solar interior from the late 1960s. One of the modern neutrino telescopes Amanda (http://www.amanda.wisc.edu/) uses the purest Antarctic ice at a depth of 3000 m at the South Pole as a working substance, another, the Baikal deep-sea neutrino telescope, uses the no less pure water of Lake Baikal at a depth of 1200 m (http://www.inr.ru/bgnt.html).

2.2 The Internal Structure of the Sun

Like other stars, the Sun was formed as a result of the gravitational compression of a cloud of interstellar gas and dust. The age of the Sun is 4.5×10^9 years, the mass is 1.99 10^{33} g, the radius $R_\odot$ is 696 Mm, the average density is 1.41×10^3 g cm^{-3}, the average distance to the Earth (1 AU) is 1.496×10^{13} cm (~215 $R_\odot$), acceleration of gravity on the surface is 2.74×10^4 cm s^{-2}, radiated energy (luminosity)—3.85×10^{33} erg s^{-1}, *sidereal period of rotation* at the equator—25.5 days. 73% of

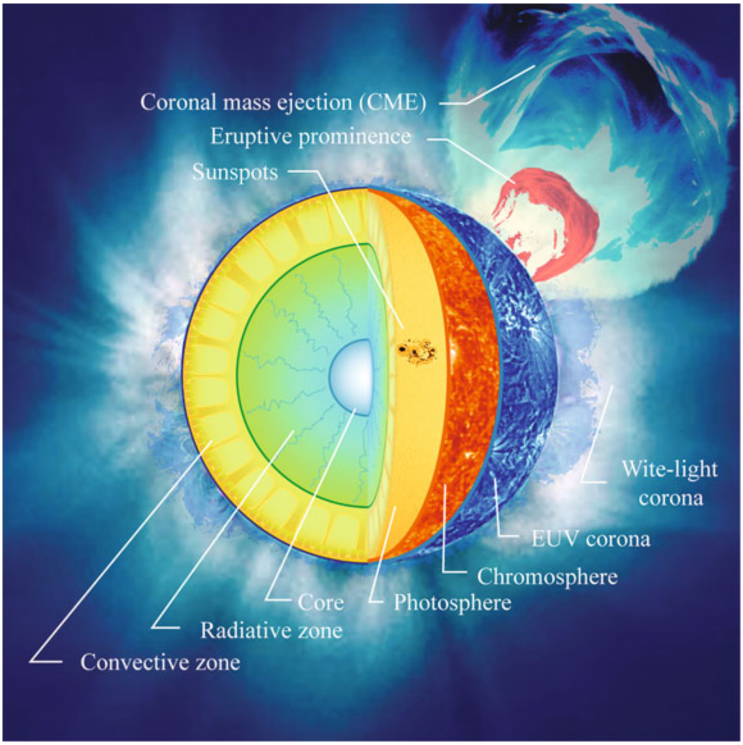

Fig. 2.1 Diagram of the internal structure of the Sun and its atmosphere

the mass of the Sun is hydrogen and about 25% is helium, that is, for every 100 hydrogen nuclei there are approximately 6 helium nuclei. The share of other elements is no more than 2% of the mass, or about 0.1% of the total number of all nuclei. These are mainly elements such as C, N, O, Ne, Fe, Ni. Their relative content is approximately the same as in the Earth's crust. Based on the difference in physical parameters and dominant processes, the Sun is divided into several spherical layers: the *core*, the *radiative zone*, the *convective zone*, the *photosphere*, the *chromosphere*, and the *corona* (Fig. 2.1).

2.2.1 Core

According to models of the internal structure of the Sun, the central region with a radius of 0.25 $R_\odot$ contains half of its entire mass. The density, which is maximum in the center (150 g cm^{-3}), decreases to the core boundary by 7 times, and the temperature (15 million K) decreases by half. Due to the high temperature and density resulting from gravitational compression, *nuclear fusion reactions* of helium from hydrogen take place in the core (Iliadis, 2007). The *proton-proton cycle* is predominant, the most probable chain of reactions of which is as follows:

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + e^{+} + \nu + 1.44\ \text{MeV},$$
$$^{2}D + {}^{1}H \rightarrow {}^{3}He + \gamma + 5.49\ \text{MeV},$$
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2{}^{1}H + 12.85\ \text{MeV}.$$

Each of the reactions is exothermic; energy is released in the form of gamma radiation and kinetic energy of particles.

Protons, being charged particles, repel each other by the Coulomb force, but they can nonetheless stick together, demonstrating the existence of another, short-range force referred to as nuclear attraction. High temperature and density are needed to bring two protons close enough together in order to overcome the repulsive electrostatic force by the quantum tunnel effect. The rate of the first reaction is extremely low even at the high densities and temperatures of the core, due to the necessity for the weak force to cause beta decay before the nucleons can adhere. The average proton in the core of the Sun waits about 9 billion years before it successfully fuses with another proton. In contrast, the time required for deuterium and helium-3 to participate in the following reactions is only about 4 s and 400 years. These two reactions are controlled by the strong nuclear force and are thus much faster.

The core generates 99% of the fusion power of the Sun, while proton-proton nuclear reactions in the core provide 99% of the energy emitted by the Sun. Photons born in the nucleus are scattered many times, leaking out. At the same time, they give up part of their energy, heating the outer layers, and become less rigid. In the end, gamma quanta turn into visible light quanta, but the time until a photon reaches the surface is about 1 million years. It is possible that there is a relic magnetic field in the core, captured during the formation of the core, since estimates of the decay time of the field (dissipation of electric currents) are comparable with the age of the Sun. In any case, this field is hardly related to what is observed on the surface and changes with a frequency of about 22 years.

2.2.2 Radiative Zone

In the layer from 0.25 $R_\odot$ to 0.7 $R_\odot$ from the center of the Sun, the temperature and density are no longer sufficient for the effective flow of thermonuclear fusion reactions, but hydrogen and helium remain completely ionized. The transparency of matter under these conditions is high, and energy is transferred by radiation. The temperature in the radiative zone varies from 8 million K to 2 million K, and the density varies from 20 g cm^{-3} to 0.1 g cm^{-3}. From the point of view of physics, this is the least interesting region of the Sun.

2.2.3 Convective Zone

When the thermal speed of electrons becomes so low that they can be captured by the nuclei of various elements, that is, recombination occurs, the transparency of the substance decreases sharply, as more and more photons are absorbed by ions. Correspondingly, the energy transfer by radiation deteriorates and the temperature gradient increases. If the temperature gradient exceeds the adiabatic gradient (Schwarzschild criterion), convective instability is excited. Due to the energy released during the recombination of electrons with nuclei, the temperature in the rising and expanding gas element of volume will fall more slowly than with simple adiabatic expansion and, therefore, the gas in this element will be hotter and lighter than the surroundings. Under the action of the Archimedean buoyancy force, the element will continue to rise, carrying energy more efficiently than radiation. The layer in which energy is carried mainly by moving matter and not by radiation extends on the Sun from 0.7 $R_{\odot}$ almost to the surface. Since convective cells come to the surface, their existence follows not only from the predictions of the theory, but also from direct observations of surface phenomena. Observations indicate the presence of three or four characteristic sizes of convective cells associated with hydrogen ionization (1 Mm), single (5–10 Mm) and double (15–30 Mm) helium ionization and height scale. The existence of giant cells with dimensions on the order of 300 Mm has been established less reliably.

Another type of motion in the convective zone is associated with differential rotation. The fact is that the angular velocity of rotation in the convective zone is not constant, as in a solid body, but varies depending on depth and latitude. Such information is provided by the analysis of the oscillations of the surface of the Sun, known as *helioseismology*. The maximum rotation speed, 1 revolution in 24.7 days (*synodic period*, as it would be measured by an observer on the Earth) is in the equatorial region at the level of 0.93 $R_{\odot}$. Up to the level of 0.75 $R_{\odot}$, called the *tachocline*, the rotation rate decreases slowly, and then in a relatively thin layer of 0.1 $R_{\odot}$ it rapidly drops to the rotation rate of the core and radiative zone (about 27 days). With increasing latitude, the rotation speed also decreases. The rotation period at the poles is about 36 days. At the base of the convective zone, in the tachocline, favorable conditions are formed for the functioning of the *solar dynamo*, the mechanism for generating a magnetic field due to the mechanical energy of plasma movement. The tubes of the magnetic field in highly conductive plasma are buoyant and, when the certain threshold field strength is reached, they float to the surface, giving rise to a whole bunch of solar activity phenomena.

2.3 Solar Atmosphere

2.3.1 Photosphere

The layer from where photons can freely exit into interplanetary space is called the photosphere (Fig. 2.2). The thickness of this layer is only of the order of 100 km,

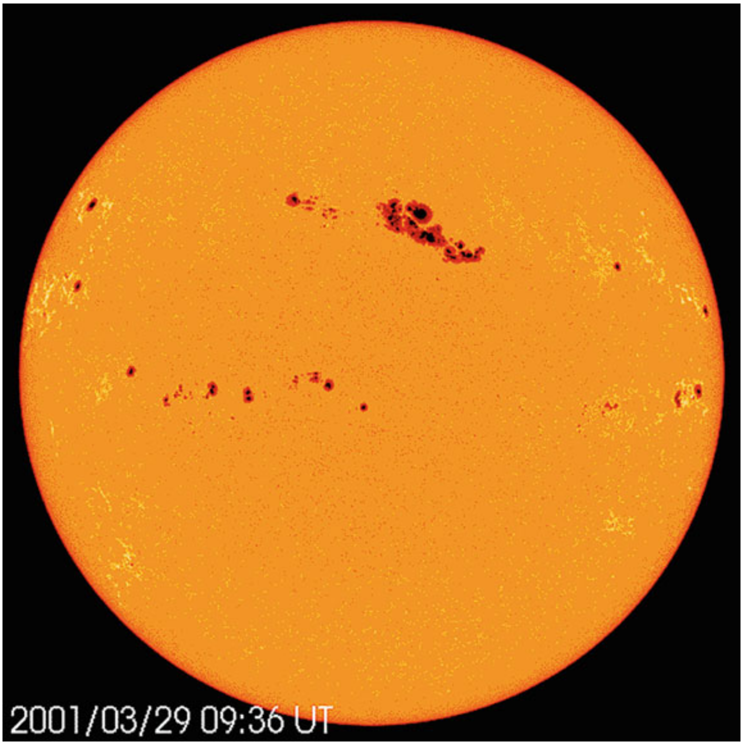

Fig. 2.2 Photosphere in solar activity maximum. (Courtesy of the *SOHO*/MDI consortium)

because the temperature here is relatively low (~6000 K), which leads to a high absorption coefficient and a small *height scale*. The density in the photosphere varies from ~10^{-7} g cm^{-3} at the lower boundary to ~10^{-9} g cm^{-3} at the upper one. The maximum emission of the photosphere falls on the visible region of the spectrum. Near the visible and infrared parts of the spectrum, the continuous radiation of the Sun is similar to the radiation of a completely black body with a temperature of ~6000 K. The most important role in the absorption and emission of visible light quanta is played by negative hydrogen ions H^-, whose concentration decreases with height even faster than the total density of the substance, due to the drop in electron concentration with decreasing temperature. It is for these reasons that we see the sharply defined edge of the Sun, the *solar limb*. The temperature in the photosphere continues to decrease with the radial distance, as in the inner layers of the Sun, which cannot be said about its upper parts of the atmosphere. The photosphere is also defined as a layer from the level, where the *optical depth* reaches unity at a wavelength of 5000 Å, to the level of the temperature minimum of ~4300 K. This distance is about 550 km. Near the edge of the solar disk, due to the very small angle between the line of sight and the spherical surface, the same optical depth is achieved closer to the surface, as a result of which higher and, hence, colder layers make a

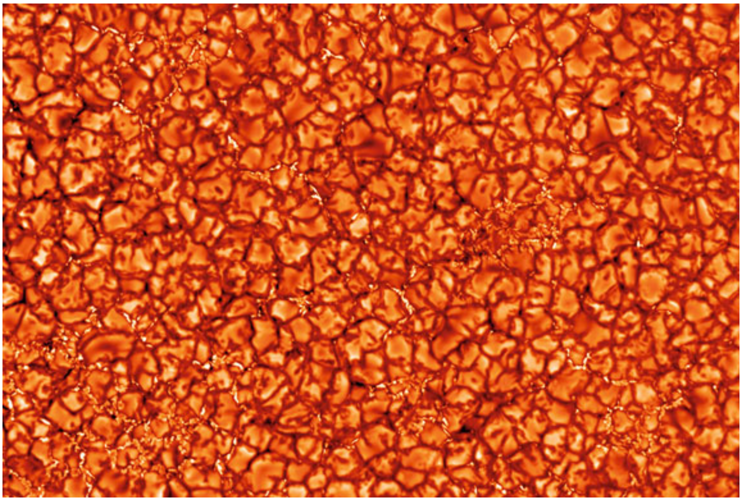

Fig. 2.3 Quiet Sun, granulation and bright points (filigree) on 2017 May 25 observed with the CHROMIS instrument at the Swedish 1-m Solar Telescope in the Ca II K 3934 Å line. (Credit: Vasco Henriques and Ainar Drews, ITA, University of Oslo)

larger contribution to the radiation. As a consequence, the brightness of the solar disk in white light decreases towards the edge.

On images of the photosphere with good spatial resolution, it can be seen that it has a cellular structure with bright irregular granules separated by darker thin gaps (Fig. 2.3). The average *granule* size is about 1 Mm, the lifetime is about 8 min, the temperature difference between the center and the boundary is at least 100 K, and the difference in brightness is about 10%. *Granulation* is a manifestation in the photosphere of the smallest-scale convection. In the center of the granule, the hot substance rises at a speed of ~0.4 km s^{-1} and then spreads horizontally at a speed of ~0.25 km s^{-1}. After cooling due to radiation, the material goes down near the borders of cells. Larger-scale convective cells, *supergranules*, practically do not manifest themselves in photosphere brightness variations, but are clearly visible in the velocity field, especially in areas far from the disk center, where horizontal motions create sufficient *Doppler shifts*.

While the granulation is always present, a number of photospheric details are transient and refer to manifestations of solar activity. They appear for a relatively short time and disappear, sometimes occurring often, sometimes rarely, depending on the phase of the solar activity cycle. The most noticeable formations are sunspots, round or oval areas 10–20 Mm in size with a brightness of only 1–15% of the brightness of the surrounding photosphere (Fig. 2.4). Around the darkest part, the *umbra* of the *sunspot*, there is a lighter wide border, the *penumbra*, consisting of dark and light penumbral filaments elongated approximately along the radius from the center of the spot. The smallest sunspots that do not have penumbra are called *pores*. The lifetime of a sunspot depends on its size and varies from several hours or days

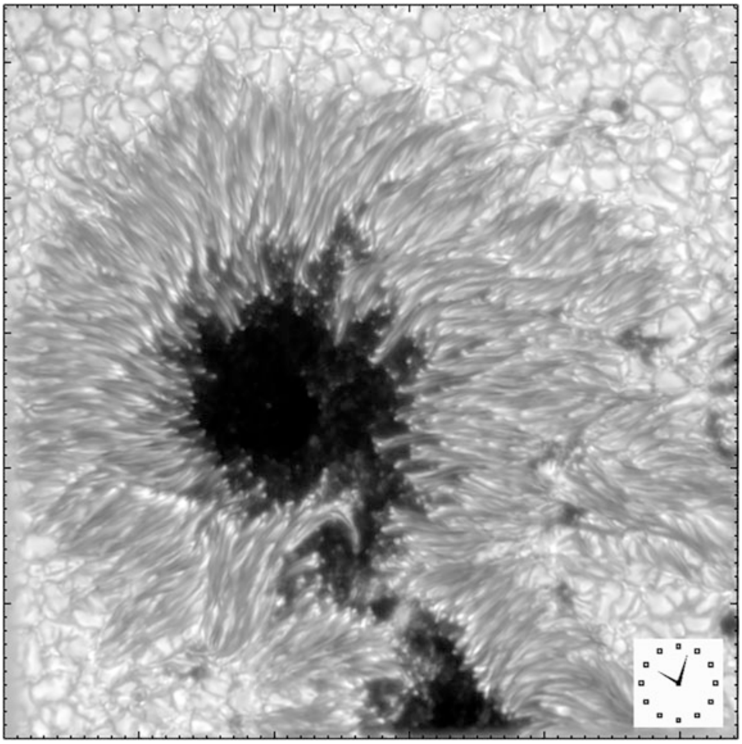

Fig. 2.4 Sunspot in AR 11302 observed on 2011 September 28 with the CRISP instrument at the Swedish Solar Telescope on La Palma. The observations were made in the Fe I 6173 Å line, which is formed in the photosphere. (Credit: Sara Esteban Pozuelo (IAA-CSIC), Luis Bellot Rubio (IAA-CSIC), Ada Ortiz (ITA, University of Oslo)

for pores to several months for large sunspots. The temperature in the umbra is 2000 K lower than in the quiet photosphere. The decrease in temperature is usually explained by the suppression of convection by the strong magnetic field present in the sunspot. The magnetic field induction is also the greater, the larger the sunspot. In pores it is about 1000 G, in large sunspots up to 3000 G.

At a not too great distance from the limb, formations are visible in the photosphere, the brightness of which is 10–20% higher than the surrounding area, called photospheric *faculae*. In the center of the disk, the faculae are indistinguishable, which indicates that the total energy flux emitted in the direction normal to the surface does not differ from the average, but the temperature in the faculae changes with height more slowly than in the unperturbed photosphere. The faculae are a conglomeration of bright facula dots, the size of which does not exceed the real resolution of telescopes (< 200 km), which line up in chains, filaments, and meanders. Separate dots increase their brightness and then fade away within a few minutes, while groups of faculae, changing, exist longer than sunspots. Most faculae are found in *active regions* near sunspots, although they are found everywhere, including polar regions. Thin elongated structures located between the granules at the border of supergranulation cells are called *filigree*. The faculae have a fairly strong magnetic field, hundreds of gauss on average, which, however, is probably concentrated in very small elements, vertical tubes with a field of ~1000 G, coinciding with the facula dots.

The photosphere rotates differentially: the equatorial regions make a complete revolution 10 days faster than polar regions. It should be borne in mind that in observations from the Earth, the period of rotation (*synodic*) differs from the period of rotation in a stationary system (*sidereal*) due to the orbital motion of the Earth.

Each atom or ion in the solar atmosphere preferentially absorbs or emits photons of certain wavelengths. The probability that a photon emitted in the photosphere will be reabsorbed and not go into interplanetary space is the greater, the closer its wavelength is to the wavelengths of the spectral lines of the Sun's atmosphere. As a result, narrow dark dips appear against the background of the continuous radiation spectrum (*continuum*), absorption lines or *Fraunhofer lines*. Some lines are formed due to absorption in the photosphere, some due to chromospheric absorption, and some lines observed from the Earth's surface appear as a result of absorption in the Earth's atmosphere, the so-called *telluric lines*.

2.3.2 Chromosphere

Above the photosphere is a more extended layer of the solar atmosphere, called the chromosphere, which radiates and absorbs only in separate spectral lines. It got its name because of the red color of the hydrogen spectral line $H\alpha$ of the *Balmer series*, which dominates its emission (Fig. 2.5). The temperature in the chromosphere increases with height up to 10^4 K, the density drops to 10^{-13} g cm^{-3}. Up to a height of ~1.5 Mm, the chromosphere is rather homogeneous, and above it consists of separate predominantly vertical gas jets, *spicules*, with a diameter of ~1 Mm, rising to a height of about 10 Mm (Fig. 2.6). The spicules are unevenly distributed over the surface; they are concentrated at the boundaries of supergranules. The substance of spicules rises, probably, along the magnetic field at speeds up to 30 km s^{-1}. Having reached its maximum height, a spicule either disappears, losing its brightness, or descends at approximately the same speed. The magnetic field in the chromosphere plays an important role both in the organization of plasma motions and in the distribution of density and temperature. The ratio of gas pressure to magnetic field pressure (*plasma* β) already in the lower chromosphere becomes less than unity and continues to decrease with height up to the very top. Compressed and held in thin magnetic tubes in the photosphere, the magnetic field in the chromosphere expands greatly, as a result of which the field in the chromosphere becomes predominantly horizontal. Magnetic field lines cover areas with a weak field inside the supergranulation cells as a *canopy*.

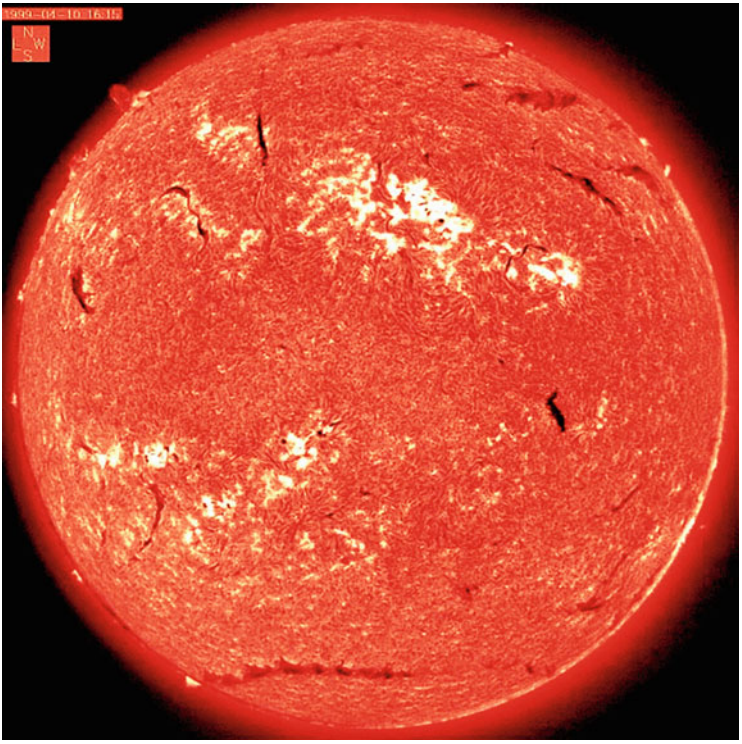

Fig. 2.5 Chromosphere observed in the Hα line. (Courtesy of the Big Bear Solar Observatory/New Jersey Institute of Technology)

The chromosphere is transparent for almost all wavelengths of visible light, except for narrow intervals close to the wavelengths corresponding to energy transitions in the electron shells of atoms and ions present in the chromosphere. In the temperature range typical for the chromosphere, the strongest absorption lines belong to ionized calcium, H and K CaII (3934 Å and 3968 Å), and hydrogen, Hα (6563 Å). The appearance of the chromosphere on the disk strongly depends not only on the spectral line in which the image was obtained, but also on which part of the line, in the core or in the wing, since different parts of the line are formed at different heights. The most noticeable details visible in all strong chromospheric lines are bright *floccules*, or *plages*, which are located above the photospheric *faculae* and are considered to be their chromospheric continuation. The plages correspond to the regions of an enhanced magnetic field (up to 800 G). Their appearance in the unperturbed region is a sure sign of the emergence of a new magnetic flux, and they disappear much later than the decay of the last sunspots of the group. As well as traces of convection of a minimum scale are clearly visible in the photosphere, the boundaries of supergranulation cells in the form of a *chromospheric network* are clearly manifested in the chromosphere. The point is that the

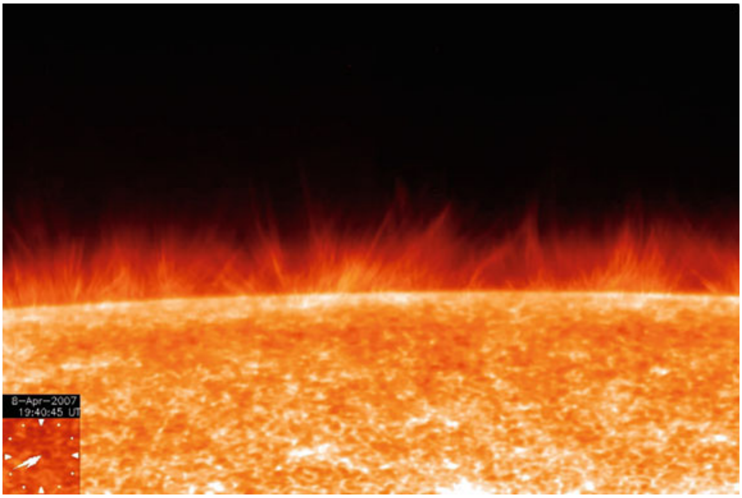

Fig. 2.6 Spicules at the solar limb on 2007 April 8 observed by the Broadband Filter Imager onboard the Japanese *Hinode* satellite with a Ca II H filter at 396.85 nm. (Credit: Joten Okamoto, NAOJ/JAXA)

convective flows, spreading near the surface of the photosphere, transfer the magnetic flux frozen into the plasma to the cell boundaries, where it is concentrated. Having penetrated into the chromosphere, this field affects the distribution of density, temperature, and velocities.

At the center of the CaII K line, the network consists of bright points lining up along the boundaries of supergranules. In the wings of the Hα line near the edge of the disk, the network is outlined by bundles of dark short threads, *dark mottles*, which are nothing but spicules observed on the limb (Fig. 2.7). In the center of the Hα line in the period of maximum activity, almost the entire disk is covered with thin dark *fibrils*, located mainly inside the supergranulation cells. Long fibrils (*threads*) connect the bright elements of the network with a field of opposite polarity, shorter ones line up in a chain between them. The most developed fibril systems are observed in active regions and their vicinity, as well as near solar *dark filaments*. Apparently, individual fibrils are sections of flux tubes within the chromosphere filled with chromospheric plasma with a density greater than in neighboring elements. And since the thickness of the chromosphere is relatively small, flat tubes with an almost horizontal field form long fibrils, and tubes that look like steep arches create short fibrils. On the whole, the orientation of fibrils characterizes the direction of the tangential to surface of the Sun component of the magnetic field vector in the chromosphere. Vertical fibrils appear to be the same as spicules. Inside the magnetic flux tube, the matter is not always and necessarily in a state of hydrostatic equilibrium. The magnetic field does not interfere with movements along the tube. As a result, fibrils are changeable, dynamic formations. The lifetime of an individual fibril

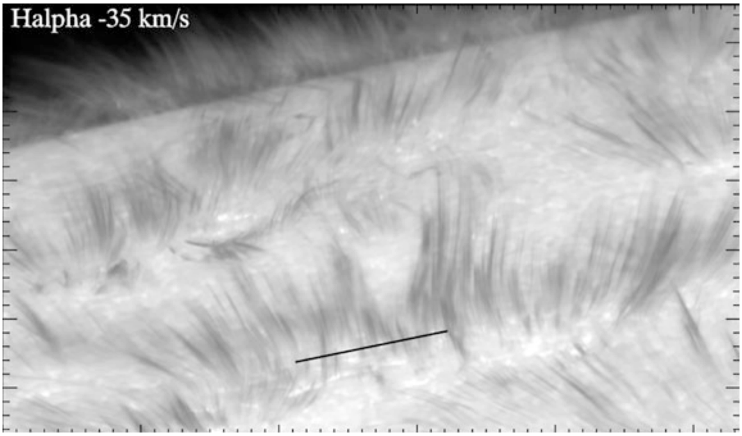

Fig. 2.7 Dark mottles in the red wing of the Hα line observed on 2010 June 27 with the Crisp Imaging Spectropolarimeter at the Swedish 1-m Solar Telescope. (Credit: Luc Rouppe van der Voort and Patrick Antolin, ITA, University of Oslo)

is only 10–20 min. However, the overall large-scale structure persists for many hours and even days.

2.3.3 Corona

The outermost part of the solar atmosphere is called the *corona*. It consists of very rarefied and hot plasma. The temperature increase to 1–2 million K typical in the corona occurs in a very narrow *transition zone*, which is not a stationary spherical layer, but rather a dynamic formation of thin shells around cold spicules penetrating into the hot corona. The mechanism of coronal heating to a temperature exceeding by two orders of magnitude the temperature of the photosphere is not completely clear. Most likely, this is the dissipation of *magnetohydrodynamic waves* that are generated by turbulence in the photosphere and the convective zone, or the dissipation of small-scale electric currents generated in the corona due to displacements of the footpoints of magnetic field lines by photospheric motions. The density in the corona is 10^{-16}–10^{-15} g cm^{-3}. In addition to the low density, hydrogen fully ionized at high temperature can neither emit nor absorb photons. The corona is visible to the naked eye only in rare moments of *total solar eclipses*, when the bright photosphere is covered by the Moon and the light scattered by the free electrons of the corona, which is a million times less bright than the direct radiation of the photosphere, becomes visible (Fig. 2.8).

The general appearance of the white-light corona changes during the 11-year *cycle of solar activity*. At the activity minimum, the corona is stretched along the equatorial plane. Its shape practically does not change from day to day, which indicates that

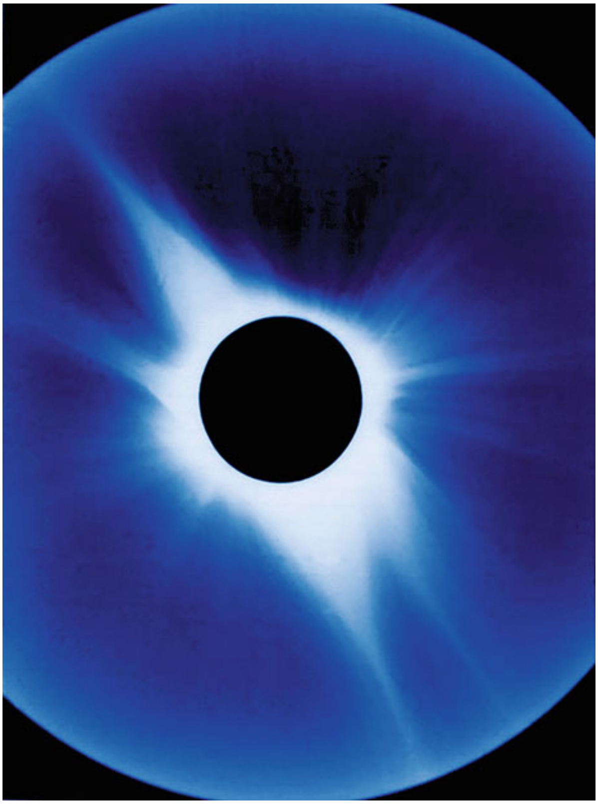

Fig. 2.8 White-light corona observed during the total solar eclipse on 11 August 1991

the axis of the Sun's rotation is also an axis of symmetry of the corona. At activity maximum, the observed shape of the corona on any particular day is on average closer to spherically symmetrical, although it can significantly change from day to day in its projection onto the plane of the sky during the rotation of the Sun. Sometimes the shape of the corona may be similar to that observed at minimum, but rotated around the line of sight through a large angle, up to 90°.

The most prominent structural elements of the white corona are *helmet streamers* or *coronal rays*. The basis of a streamer is an arcade of loops over a large-scale *polarity inversion line (PIL)* of the photospheric magnetic field. At a height of 1–2 $R_\odot$ above the limb, the tops of the arches sharpen, forming a *cusp structure*, and then the streamer contracts into a narrow coronal ray. Below the high-density bulbous dome there is a low-density *cavity*, inside of which there is usually a *quiescent prominence*. *Polar plumes* are structures on a somewhat smaller scale than streamers. These ray-like formations are especially well seen in the polar regions of the Sun during the period of minimum activity.

In addition to the white light continuum, the emission lines of the corona are known since the end of the nineteenth century. For a long time, they could not be identified with any of the elements known on the Earth. The mysterious lines have been attributed to a hypothetical element, *coronium*. Only in the middle of the twentieth century, it was found that the coronal lines in the visible spectral range are emitted by highly ionized ordinary elements Fe, Ni and Ca in forbidden electron transitions.

The share of the corona in the total solar radiation flux is not as small in all ranges of the spectrum as in the visible light. In the radio range, radiation is emitted and absorbed mainly by free electrons, and the corona has a large optical depth here. Radio telescopes make it possible to observe the corona at any time, regardless of weather conditions, but very large instruments (due to the long wavelength) are needed to obtain a sufficiently high spatial resolution. Only in the last decades, the largest solar radio telescopes, usually *radio interferometers*, began to obtain radio images of the corona. Among them are primarily the Japanese Radio Heliograph in Nobeyama (Nakajima et al., 1994; http://solar.nro.nao.ac.jp/norh/) and the Siberian Solar Radio Telescope (Smolkov et al., 1992; http://ssrt.iszf.irk.ru/indexru.shtml). At the other end of the spectrum, in the extreme ultraviolet and X-ray regions, the corona also becomes the main source of radiation despite its low density. This is due to the fact that this region accounts for the maximum thermal radiation at temperatures of millions of degrees. Numerous closely spaced coronal emission lines in this range make it possible to determine the temperature and abundance of elements. The only problem is that the Earth's atmosphere does not transmit short-wave radiation and the instruments must be placed outside of it. A number of space missions have successfully solved this problem: *Yohkoh* (Acton et al., 1992), (http://www.isas.jaxa.jp/home/solar/main.html), the *Solar and Heliospheric Observatory (SOHO)* (Domingo et al., 1995; http://sohowww.nascom.nasa.gov/), the *Transition Region and Coronal Explorer (TRACE)* (Handy et al., 1999; http://trace.lmsal.com/), *Hinode* (Kosugi et al., 2007; https://www.nasa.gov/mission_pages/hinode/mission.html), *Geostationary Operational Environmental Satellites (GOES)* (http://sxi.ngdc.noaa.gov/), *Complex Orbital Near-Earth Observations of the Solar Activity (CORONAS)* (Kuznetsov, 2014; http://coronas.izmiran.ru/F/), the *Solar Terrestrial Relations Observatory (STEREO)* (Kaiser et al., 2008; https://stereo.gsfc.nasa.gov/) and the *Solar Dynamic Observatory (SDO)* (Pesnell et al., 2012; https://sdo.gsfc.nasa.gov/).

The coronal plasma, like the chromospheric plasma, is controlled by the magnetic field. Moreover, in contrast to the chromosphere, which gives a "cross-section" of the magnetic field, the X-ray image of the corona is "three-dimensional" (3D). The temperature of the corona is a hundred times higher than in the chromosphere, respectively, the *height scale* is also a hundred times greater. Bright thin *coronal loops* rise high above the surface of the Sun and are clearly visible throughout their length as in an image taken by the *Atmospheric Imaging Assembly (AIA)* (Lemen et al., 2012) on board *SDO* (Fig. 2.9). The brightest loops are seen in the inner parts of active regions, where the field is stronger. The loops do not cover the entire disk; there are dark structureless areas separating loop systems. It is believed that the field lines originating in dark X-ray regions do not return back to the surface, but go into interplanetary space. Such areas of open field lines, which are dark in X-rays, are called *coronal holes*. The outer layers of the isothermal corona cannot be in

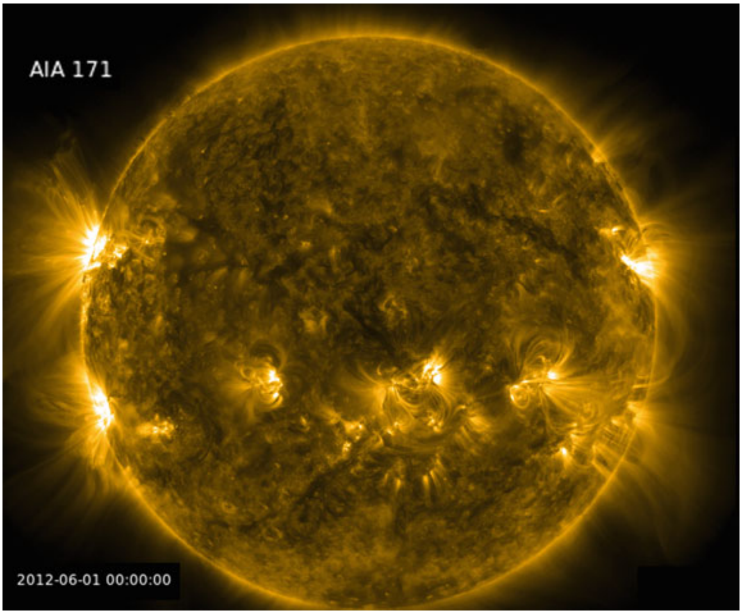

Fig. 2.9 EUV image of the solar corona in the *SDO*/AIA 171 Å channel on 2012 June 01. (Courtesy of the NASA/*SDO*/AIA science team)

hydrostatic equilibrium because the gravitation decreases as the square of the heliocentric distance r. The *height scale* $\Lambda(r) = k\ T\ r^2/m\ g\ R_{\odot}^2$, which is equal to one tenth of the solar radius in the lower corona, is compared with it in the outer corona ($r \sim 3\ R_{\odot}$) and continues to increase further. Gravity is thus unable to constrain the coronal plasma, and it expands continuously into interplanetary space, forming the *solar wind*. Flux tubes with both ends connected to the surface are capable of retaining hot coronal plasma and serve as magnetic traps. The tubes "open" into the interplanetary medium are continuously emptied, so they have a lower density and temperature due to gas expansion. Coronal holes are the sources of the highest speed solar wind streams.

References

Acton, L., Tsuneta, S., Ogawara, Y., Bentley, R., Bruner, M., Canfield, R., Culhane, L., Doschek, G., Hiei, E., & Hirayama, T. (1992). The *Yohkoh* mission for high-energy solar physics. *Science, 258*, 618–625.

Domingo, V., Fleck, B., & Poland, A. I. (1995). The SOHO mission: An overview. *Solar Physics, 162*, 1–37.

Handy, B. N., Acton, L. W., Kankelborg, C. C., Wolfson, C. J., Akin, D. J., Bruner, M. E., Caravalho, R., Catura, R. C., Chevalier, R., Duncan, D. W., Edwards, C. G., Feinstein, C. N.,