Chapter 1

Overview of the Sun

The Sun is sometimes told to be a typical, rather boring main sequence star. While it is a rather average late type star, it is yet far from uninteresting. On the contrary, the Sun is a very complicated object exhibiting highly variable and complex activity that cannot be simulated in laboratories and even the most powerful computers are still far away from the capacity of a detailed modelling of the largely variable parameter ranges from the hot interior of the Sun to its cool surface and again to the hot corona. The Sun is not unimportant either. For an astronomer it is the only star that can be observed in great detail and, of course, its existence and properties are critical to us on Earth.

The modern picture of the Sun started to develop in the dawn of modern physical sciences when *Galileo Galilei*, one of the first developers and users of the telescope, found sunspots on the solar disc in about 1610–1613. However, after this the development remained rather slow. In 1802 *Hyde* discovered that the solar spectrum contained several absorption lines which were later catalogued by *Fraunhofer*. In 1844 *Schwabe* showed that the sunspot activity varies in an 11-year cycle. In 1859 *Carrington* and *Hodgson* independently observed a solar flare in white light. They noted that 17 hours after the flare a magnetic storm commenced in the near-Earth environment. The secondmost common element in the universe was identified in 1868 in the solar spectrum by *Lockyer* and later given the name helium.

Most of our present understanding of the Sun did not exist before the 20th century. Among the first major advances were *Hale's* measurements of intense magnetic fields in the sunspots in 1908, showing that whatever generated the solar activity, it was closely related to magnetism and was highly variable. One key enigma remained, however. At the end of the 19th century lord *Kelvin* had demonstrated that the largest imaginable energy source for the solar radiation, the gravitational binding energy of the Sun would not be sufficient for more than 20 million years at the present solar luminosity, which already at that time was considered much too short. To solve this problem understanding of the nuclear forces had to be obtained, and in 1938 *Bethe* and *Critchfield* explained the dominant proton-proton reaction chain that powers the Sun. For this and other discoveries of energy production in stars Bethe was awarded the Nobel Prize in Physics in 1967.

From the 1960's the Sun has been possible to observe from space. The present years can be described as a golden age of solar research. The X-ray images from the Japanese Yohkoh satellite launched in 1991 have made the hot active Sun visible for a whole sunspot cycle. In 1995 the European Space Agency (ESA) and NASA of the United States launched the joint SOHO spacecraft to the Lagrangian libration point L1 where it makes continuous observations of the Sun in particular in UV and optical wavelengths. High-resolution measurements of the Zeeman effect provide detailed observations of the solar magnetic field and detailed Doppler measurements give unprecedented information about solar oscillations facilitating mapping of the interior structure of the Sun using a method called helioseismology. In 1998 the NASA Small Explorer series satellite, called TRACE, started making very high-resolution observations of small-scale phenomena in the solar atmosphere and corona and in 2002 another Small Explorer, RHESSI, was launched for studies of particle acceleration and explosive energy release in solar flares. Web-sites to these missions are:

Yohkoh:	http://www.lmsal.com/SXT/
SOHO:	http://sci.esa.int/soho
TRACE:	http://vestige.lmsal.com/TRACE/
RHESSI:	http://hesperia.gsfc.nasa.gov/hessi/

These space missions have provided a wealth of new data for further research and paved way to future, even more advanced, missions to study the Sun. NASA is preparing to launch a two-spacecraft mission called STEREO in November 2005. The satellites will orbit the Sun on the same orbit as the Earth, one ahead the Earth and the other behind. This will allow for stereoscopic observations of the solar activity. ESA is planning to send the Solar Orbiter spacecraft to an inclined orbit around the Sun reaching down to a distance of about 40 solar radii, i.e., some 20 % of the Sun-Earth distance. Presently the mission is scheduled to begin in the 2014.

Also the ground-based solar observatories contribute to the present progress in understanding the Sun. The large radio telescopes are able to map the cyclotron radiation from the energetic electrons in solar eruptions and in the visible wavelengths penetrating through the atmosphere, the Earth is still the most cost-efficient place to make the observations. And in 2002 the Sudbury neutrino observatory conclusively showed that the solution to the long-standing solar neutrino problem really lies in the physics of neutrinos and thus there is no need for any fundamental changes in the models of the solar interior.

An extra boost to solar research has come during the last 10 years from an emerging sector of space research, space weather. The term refers to temporally changing conditions in the Sun, solar wind, magnetosphere, ionosphere, and atmosphere, which can be hazardous to technological systems in space and on ground and may threaten human life or health. The Sun is the driver of space weather and in order to reduce the hazardous consequences either by system design or reliable forecasting we need to learn much more details of solar physics. Space weather requires continuous monitoring of the Sun and solar wind. A useful web-site for real-time information is

http://www.sec.noaa.gov

1.1 Basic facts about the Sun

Let us begin by summarizing some basic numbers about the Sun. These will be discussed in greater detail later in the text.

- Age = 4.5×10^9 years
- Mass, $m_\odot = 1.99 \times 10^{30}$ kg ($\approx$ 330 000 m_E, mass of the Earth)
- Radius, $r_\odot$ = 696 000 km ($\approx$ 109 R_E, the Earth's radius)
- Average density = 1408 kg/m^3 = 1.408 g/cm^3
- Average distance from the Earth (1 AU) = 150×10^6 km (215 $r_\odot$)
- Gravitational acceleration on surface = 274 m/s^2
- Escape velocity on surface = 618 km/s
- Luminosity = 3.84×10^{26} W
- Rotation period at equator = 26 days
- Mass loss rate $\approx 5 \times 10^9$ kg/s
  – radiation: 4×10^9 kg/s; solar wind: 1×10^9 kg/s
- Effective black body temperature = 5778 K

Spectral classes

Stars are divided to several spectral classes according to decreasing effective temperature: O, B, A, F, G, K, M, R, N,$\cdots$. These are further divided to subclasses. The Sun belongs to class G2.

Exercise: Hertzsprung-Russell diagram

With help of literature, get acquainted with the so-called Hertzsprung-Russell diagram.

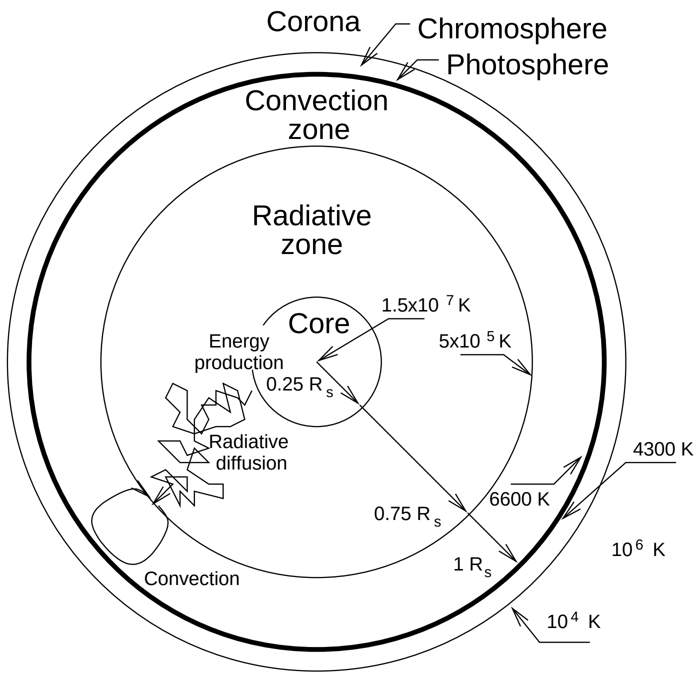

Figure 1.1: The Sun.

Structure of the Sun

Figure 1.1 shows the large scale structure of the Sun as we know it today. The energy is produced in the hot central core. Outside the core the energy flows outward radiatively to the distance of about 0.72 $r_\odot$. There the radiation is no more efficient enough and convective motion takes over the energy transfer. The thin surface of the Sun absorbs almost all the the energy and radiates it out as a black body at the temperature of 5778 K.

1.2 Where is the Sun?

The Sun is located in a spiral arm of our galaxy, the Milky Way. For us it is of importance to determine the distance to the Earth. From Kepler's third law we get

$$\frac{a^3}{T^2} = \frac{Gm_\odot}{4\pi^2}\left(1 + \frac{m_E}{m_\odot}\right) , \tag{1.1}$$

where a is the semimajor axis of the Earth, T the orbital period, and G the gravitational constant (6.673×10^{-11} m^{3}s^{-2}kg^{-1}). If we knew $m_\odot$ and T we would get a (because $m_E \ll m_\odot$).

Traditionally a was determined by triangulation with two planetary bodies. From Kepler's law we can derive

$$\left(\frac{a_1}{a_2}\right)^3 = \left(\frac{T_1}{T_2}\right)^2 \frac{1 + m_1/m_\odot}{1 + m_2/m_\odot} . \tag{1.2}$$

Now we need the masses m_i in units of $m_\odot$. These are obtained from mutual perturbations of the the planetary orbits.

Since 1961 more accurate determination has been obtained using radar echos, but not from the Sun as it is not a very homogeneous reflector. Instead echos from other planets are used and put into Kepler's law. This gives us the **light time** for the unit distance τ_{AU}

$$\tau_{\mathrm{AU}} = 499.004782 \pm 0.000006 \text{ s} . \tag{1.3}$$

Using the **exact** value of the velocity of light $c = 299\,792\,458$ m/s we get the length of **the astronomical unit** (AU):

$$1\,\mathrm{AU} = 149\,597\,870 \pm 2 \text{ km} . \tag{1.4}$$

Thus, for practical purposes the mean distance to the Sun is 149.6 million kilometers, which we will hereafter use as the value of AU. Note that the Earth's orbit is elliptical:

Perihelion in January:	147.1 million km
Aphelion in July:	152.1 million km

Exercise

What distance on the center of the solar disc does one arcsec (1") correspond to (at perihelion, at aphelion, on average)?

1.3 Mass of the Sun

If a, T, $m_E \ll m_\odot$ are known, Kepler's law gives $Gm_\odot$ with an accuracy of about 8 significant numbers. But G is the most inaccurately known natural constant, whose official error margin was increased so late as in 1998! Consequently we know the present solar mass within an error of about 0.15 per cent:

$$m_\odot = (1.989 \pm 0.003) \times 10^{30} \text{ kg} . \tag{1.5}$$

At present mass is lost 4×10^9 kg/s through radiation and 10^9 kg/s is carried away by the solar wind.

Exercise

How much mass has the Sun lost during its lifetime assuming the present loss rate?

1.4 Size of the Sun

The angular semidiameter of the solar disc is 960.0 ± 0.1" (i.e., the angular diameter is 32'$\approx 0.5°$). The surface is defined to be a little deeper in the atmosphere. In calculations of these lectures we use for the radius

$$r_\odot = 696\,000 \text{ km}\,. \tag{1.6}$$

Thus the mean density is 1408 kg/m^3 and for the gravitational acceleration on the surface we find

$$g_\odot = \frac{Gm_\odot}{r_\odot^2} = 274 \text{ ms}^{-2}\,. \tag{1.7}$$

1.5 Luminosity

The solar constant S expresses the total irradiance at the mean distance of the Earth. S can be measured directly and is usually given as

$$S = 1367 \pm 3\,\text{Wm}^{-2}\,. \tag{1.8}$$

S is related to **the luminosity** of the Sun $L_\odot$ by

$$L_\odot = 4\pi\,\text{AU}^2\,S = (3.844 \pm 0.010) \times 10^{26}\,\text{W}\,. \tag{1.9}$$

Note that **the solar constant is not constant**. The luminosity of the newly-born Sun was about 72% of its present value. Furthermore, the present "solar constant" varies by a factor of

- 10^{-6} over minutes
- 2×10^{-3} (0.2 %) over several days
- 10^{-3} over solar cycle (exact value uncertain)

The physical reasons and apparent periodicities of these variations are not fully understood.

Accurate determination of S requires that it is observed above the dense atmosphere that absorbs most of the radiation in ultraviolet (UV) and infrared (IR) wavelengths. Recent inter-calibrations between various space observations indicate that the on average $S \approx 1366$ Wm^{-2} around solar minima and $S \approx 1367$ Wm^{-2} near solar maxima. However, around solar maxima the irradiance varies by several Wm^{-2} and thus the conservative error estimate in (1.8) is appropriate.

Note that the solar variability seems about a factor of three weaker than typical variations in other Sun-like stars. It is possible that the luminosity variations in the solar polar regions cannot be measured quite correctly from the nearly equatorial direction whereas the average viewing angle of other stars is about 30° off the equatorial plane. However, most likely the present Sun is less variable than typical Sun-like stars.

Luminosity can be given in terms of effective temperature defined by

$$L_{\odot} = 4\pi r_{\odot}^2 \sigma T_{\text{eff}}^4 \tag{1.10}$$

where $\sigma = 5.6704 \times 10^{-8}\,\text{Wm}^{-2}\text{K}^{-4}$ is **the Stefan-Boltzmann constant**. For the Sun $T_{\text{eff}} = 5778 \pm 3$ K.

Exercise

The apparent brightness of a star is usually given in terms of magnitude. Explain the concepts of **apparent magnitude** and **absolute magnitude**. What is the absolute magnitude of the Sun?

Exercise

Derive the effective temperature starting from Planck's law

$$B_{\lambda} = \frac{2hc^2}{\lambda^5 (e^{hc/\lambda k_{\text{B}} T} - 1)}\,. \tag{1.11}$$

1.6 Solar spectrum

1.6.1 Spectrum of a star

In 1859 Kirchhoff formulated the general laws governing the production of spectrum:

1. The ratio of emissivity to absorptivity is independent of the composition of the material and depends only on the temperature and wavelength.

2. An opaque body radiates a continuous spectrum.
3. A transparent gas radiates an emission spectrum that is distinct for each chemical element.
4. An opaque body surrounded by a gas of low emissivity shows a continuous spectrum crossed by absorption lines corresponding the spectrum of the gas.
5. If the gas has high emissivity, the continuous spectrum will be crossed by bright lines

Kirchhoff considered solid bodies as continuous emitters but the laws are valid for stars as well. The increasing density toward the stellar surface makes them opaque because the various absorption processes jointly block the radiation at all frequencies. This takes place in the photosphere from which the continuous black-body spectrum originates. We will later discuss the opacity of the Sun more in detail.

The same spectral line may show both as an emission and as an absorption line. An important example in the Sun is the **hydrogen Balmer series line** at 656.3 nm (Hα). In the photosphere the line is an absorption line whereas in the tenuous chromosphere it is an emission line. Thus by using a narrow band-pass filter at this frequency we observe the chromosphere without the photosphere background.

1.6.2 Irradiance, energy flux, and intensity

The solar irradiance $S(\lambda)$ is the energy flux observed at a given distance (in our case 1 AU) per unit area, time, and wavelength interval. It is related to the energy flux $F(\lambda)$ at the solar surface simply by

$$r_\odot^2 F(\lambda) = \mathrm{AU}^2\, S(\lambda)\,. \tag{1.12}$$

The second important quantity is **the intensity** $I(\theta,\phi,\lambda)$ (or $I(\theta,\phi,\nu)$), i.e., the energy emitted per unit area, time, wavelength/frequency interval, and solid angle (in SI-units $\mathrm{Jm^{-2}s^{-1}m^{-1}sr^{-1}}$ or $\mathrm{Jm^{-2}s^{-1}Hz^{-1}sr^{-1}}$). θ is the polar angle from a given direction and ϕ the azimuthal angle around the same direction. Note that the wavelength/frequency dependence is often denoted by $I_\lambda(\theta,\phi)$ or $I_\nu(\theta,\phi)$.

1.6.2.1 Exercise

Show that

$$\lambda I_\lambda = \nu I_\nu\,. \tag{1.13}$$

In the following, we assume no azimuthal variations and drop the ϕ-dependence. Thus the intensity depends on angular distance θ from the direction perpendicular to the solar surface. The integral of $I(\theta,\lambda)\cos\theta$ over all outward directions ($\cos\theta > 0$) yields **the energy flux** $F(\lambda)$

$$F(\lambda) = \pi \int_{-\pi/2}^{\pi/2} I(\theta,\lambda)\cos\theta\sin\theta\,d\theta \equiv \pi\overline{I}(\lambda)\,. \tag{1.14}$$

We often denote $\mu = \cos(\theta)$ when the integral above reads

$$\overline{I}(\lambda) = 2\int_0^1 I(\mu,\lambda)\mu\,d\mu = 2I(1,\lambda)\int_0^1 \frac{I(\mu,\lambda)}{I(1,\lambda)}\mu\,d\mu\,. \tag{1.15}$$

To measure $F(\lambda)$ we must either measure $\overline{I}(\lambda)$ directly from all parts of the solar disc, or the **central intensity** $I(1,\lambda)$ and the **limb darkening** function $I(\mu,\lambda)/I(1,\lambda)$. The latter method has the advantage that only a relative measurement of the diffuse light is needed.

1.6.3 Visible spectrum

Most of the solar energy is irradiated in the visible and near-infrared parts of the spectrum. Figure 1.2 shows the visible spectrum. The red side of the spectrum is almost continuous black-body spectrum with some strong absorption lines, e.g., Hα at 656.3 nm. On the blue side there are more absorption lines.

1.6.4 Infrared spectrum

About 44% of the electromagnetic energy is emitted at $\lambda > 0.8\,\mu$m. The spectrum is approximately thermal and can be represented by **the Rayleigh-Jeans law**

$$S(\lambda) \simeq 2ck_B T\lambda^{-4}(r_\odot/\mathrm{AU})^2\,. \tag{1.16}$$

The infrared spectrum is efficiently absorbed by water vapor in the Earth's atmosphere.

1.6.5 Radio spectrum

Radio wavelengths are longer than 1 mm. Instead of wavelength, frequency is often used to characterize the emissions. Recall the simple conversion formula $\lambda(\mathrm{m}) = 300/f(\mathrm{MHz})$. Thus, e.g., 1 mm $\leftrightarrow$ 300 GHz. Figure 1.3

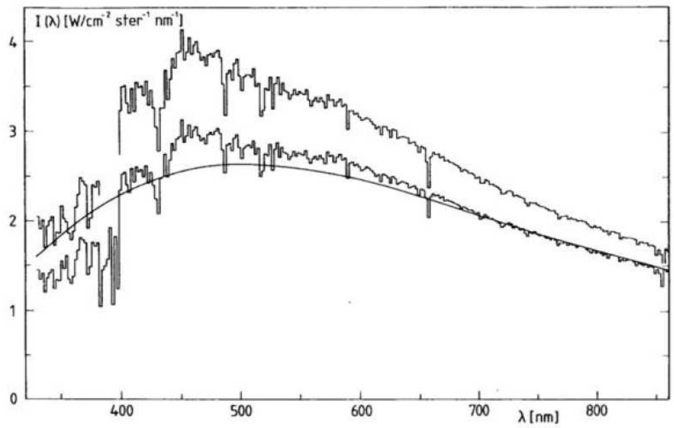

Figure 1.2: Central intensity (upper curve) and mean intensity (lower curve) at the visible wavelengths. The solid line is the black-body spectrum at the temperature 5777 K.

presents the solar radio emissions in terms of flux per frequency interval. The figure illustrates that the Sun is strongly variable at these wavelengths. The reason for this variability is that the radio emissions originate from non-thermal plasma processes in the solar atmosphere, chromosphere, and corona. During strong solar disturbances the radio emissions can exceed the quiet levels by several orders of magnitude. Note also that the slope at longest wavelenghts for the quiet Sun corresponds to higher temperatures (10^6 K) than the main black body radiation. This tells that the chromosphere and corona are much hotter than the Sun itself.

1.6.6 Ultraviolet and shorter wavelengths

Figure 1.4 illustrates the UV spectrum. Absorption lines are dominant down to 210 nm. At shorter wavelengths the intensity is reduced to correspond to the temperature of 4700 K. This reduction is due to absorption by the ionization of Al I. (Recall the standard notation: Al I represents the non-ionized aluminum, Al II is the same as Al^+, Al III is Al^{2+}, etc.) Below 150 nm emission lines start to dominate the spectrum. The strongest is the hydrogen Lyman α line centered at 121.57 nm. Its average irradiance 6 mWm^{-2} is as much as all other emissions below 150 nm together.

At short wavelengths the spectrum becomes highly variable illustrating nonuniform distribution of the emission sources in the solar atmosphere. This nonuniformity is both spatial and temporal. The wavelength band

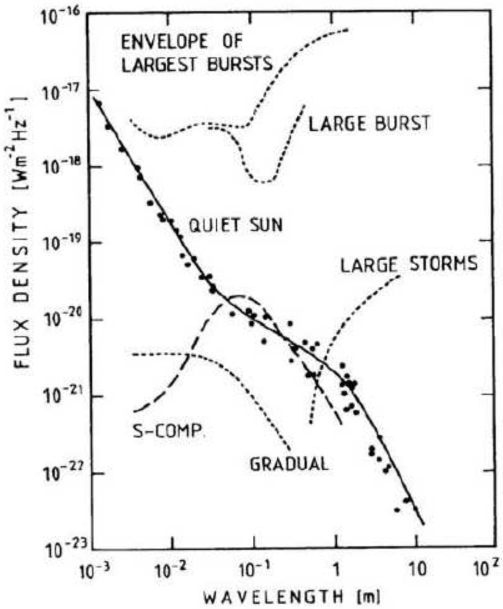

Figure 1.3: Solar radio emissions. Dots and the solid curve represent the quiet Sun, the dashed line (S-comp.) is a slowly varying component correlated to the solar cycle, and the dotted lines illustrate the rapidly varying events in the solar atmosphere.

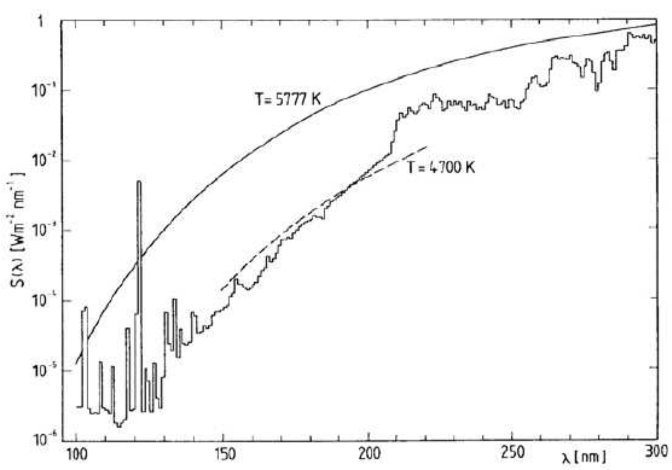

Figure 1.4: Solar UV spectrum down to 100 nm.

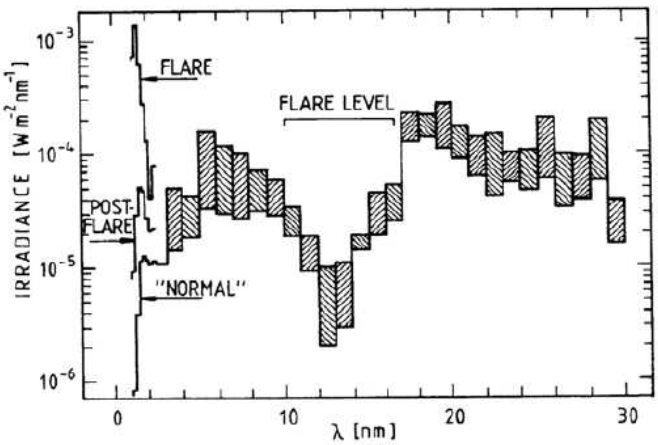

Figure 1.5: EUV and soft X-ray spectrum. The shaded intervals represent the variation without flares. The flare level is indicated. Note also the strong effect of flares in at wavelengths below 2 nm.

below 120 nm is called extreme ultraviolet (EUV). These emissions come both from neutral atoms and from ions up to very high ionization levels, e.g. Fe XVI (i.e., Fe^{15+}) in the solar corona. This makes it possible to study a wide range of temperatures from 8000 K to 4×10^6 K from the chromosphere to the corona. This is utilized by several instruments of the SOHO and TRACE spacecraft.

Solar flares increase the EUV and soft X-ray (0.1 nm – 10 nm) spectrum quite considerably (Figure 1.5). Also hard X-rays and γ-rays are emitted in these processes.