Chapter 1

Introduction

1.1 The laboratory at our doorstep

One of the main differences between astrophysicists and most other physicists is that the former cannot reproduce and study their research objects in the laboratory. We depend on what we get by observations. Photons from all parts of the Universe are the messengers that carry information about distant objects to us. Naturally, that information can be incomplete and difficult to obtain. Among the astrophysicists, solar physicists are in a somewhat privileged situation, as their study-subject is among the closest in our universe. The Sun is the only star of which the surface can be spatially resolved in detail by direct observations, allowing us to study fine structures as small as several hundred kilometers. Further, it is constantly monitored by both, ground based and space born instruments which deliver gigabytes of data every day. In some sense one could call the Sun a laboratory at our doorstep. We cannot change the laboratory setup, but we can study physical processes which may also take place elsewhere in the Universe, for example particle acceleration, in great detail.

1.1.1 A century of solar coronal observations

Because of its closeness, 1 AU or $1.469{\cdot}10^8$ km, the Sun can be and has been studied in more detail than any other star. Large sunspots are observable by the naked eye. Therefore, first observations of sunspots are passed down by the Chinese from 800 BC. With a simple backyard telescope and an Hα filter, one can already observe details such as prominences and filaments. To observe the solar corona, the bright photospheric emission has to be masked. This happens naturally during a solar eclipse. Coronal observations independent of a solar eclipse became possible with the construction of the first coronagraph by Bernard Lyot in 1930. A decade later, solar radio astronomy was born with the first detection of solar radio waves (Hey 1946). Since then, radio spectrometers all over the world have been observing the Sun from centimeter to meter-wavelengths. ETH Zürich has been operating radio spectrometers since 1972, the latest being Phoenix-2, the first digital instrument in the microwave band (Messmer et al. 1999). With the development of radio interferometry, the first radioheliograph was built in 1968 at the Culgoora radio observatory (Labrum 1972). Followed by an observatory near the Japanese village of Nobeyama (Nakajima et al. 1994) and the Naçay radioheliograph (Kerdraon & Delouis 1997).

Radio observations are relatively easy to obtain in the sense that the observed wavelengths are not significantly affected by atmospheric absorption. High quality optical observations are possible from the ground using techniques such as adaptive optics to account for atmospheric disturbances. Higher energetic electromagnetic radiation from extreme ultra-violet (EUV) to X-rays and γ-rays however, is absorbed in the upper earth atmosphere, requiring observations from space. Therefore, a whole new world of solar observations opened up with the beginning of the space age. A multitude of satellites has observed the Sun in wavelengths ranging from optical to EUV and as far as X-rays and γ-rays in the last half a century. The first X-ray observations of the Sun were made in the nineteen-forties on rockets. The first satellites to observe the Sun in EUV and X-rays up to γ-rays were the Orbiting Solar Observatories (OSO 1-8) which observed energies up to 10 MeV. They were complemented by the ESA TD-1A mission (van Beek & de Feiter 1973) and followed by EUV and soft X-ray telescopes on Skylab (Vaiana et al. 1977). The Solar Maximum Mission (SMM, Orwig et al. 1980) was the first satellite to observe the Sun over a full activity-cycle. The GOES satellites of the National Oceanic and Atmospheric Administration (NOAA) are geostationary weather satellites with an additional soft X-ray monitor that measures the solar X-ray emission (Garcia 1994). They have been providing a 24 hour coverage of solar X-ray observations for thirty years. Nowadays, the GOES classification is the main classification scheme used

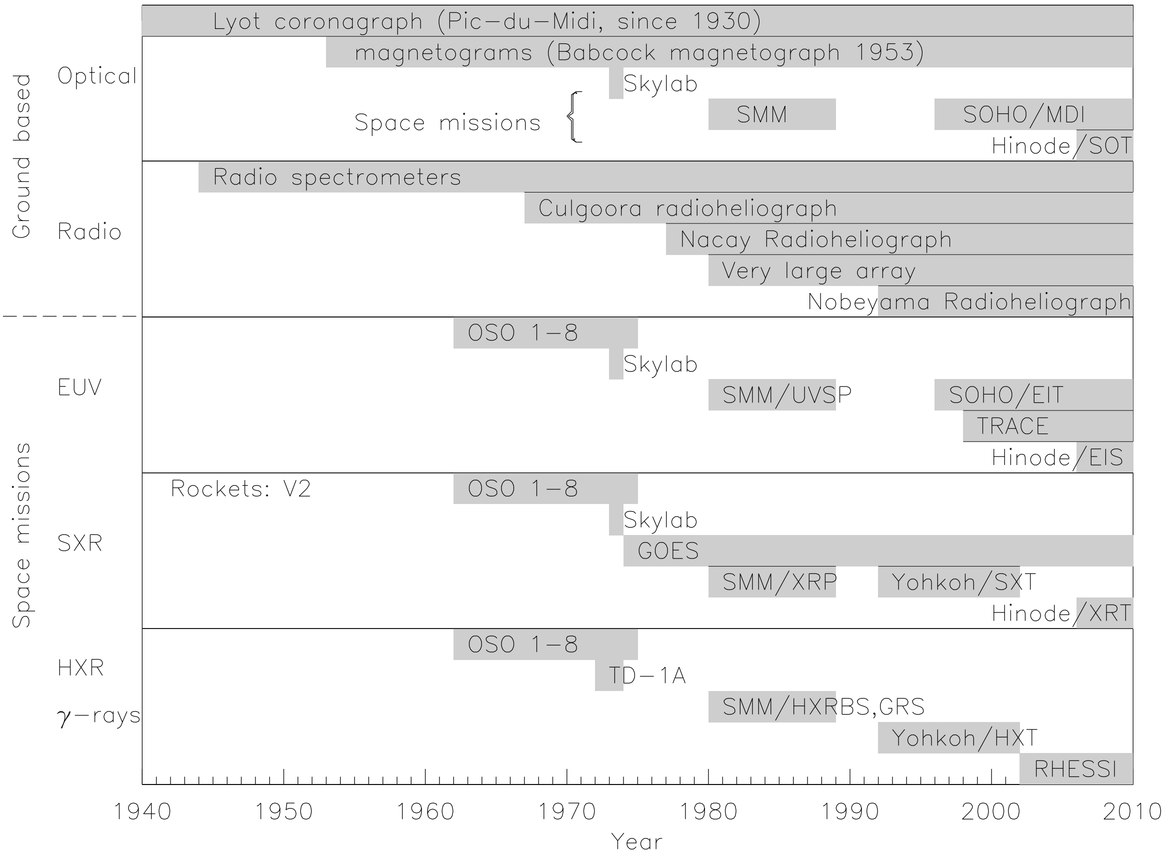

Figure 1.1: Solar observatories, ground based and space borne in the last century (following Aschwanden 2005)

for solar flares. The size of a flare is defined as its peak flux intensity in Wm^{-2} in the GOES 1-8 Å channel. Each order of magnitude in the intensity is associated with a letter as shown in Table 1.1.

In recent years, the most important mission for solar X-ray observations was RHESSI (Lin et al. 2002), currently the only solar instrument covering the wavelength range from hard X-rays to γ-rays. In 2006, the Japanese Hinode mission was successfully launched, carrying an X-ray telescope which observes the soft X-ray (thermal) regime (Golub et al. 2007). An overview of some of the important solar coronal observatories in the last 70 years is given in Fig. 1.1.

The spatial and spectral resolution of the satellites has improved considerably over the past decades. For example, the HXT instrument on the

Flux [Wm^{-2}]	GOES class
10^{-8}	A1
10^{-7}	B1
10^{-6}	C1
10^{-5}	M1
10^{-4}	X1
10^{-3}	X10

Table 1.1: Overview of the GOES flare classification scheme. Intermediate classes are eg. $5{\cdot}10^{-7}$ Wm^{-2} $\Leftrightarrow$ B5.

Yohkoh satellite (Kosugi et al. 1992) provided three energy bands in the energy range from 23 keV to 93 keV (23-33-53-93 keV), whereas RHESSI provides a spectral resolution of about 1 keV in that energy range, resulting in much more detailed spectra. Despite or just because of the increasing amount and quality of observational data, many questions in solar physics still remain unanswered.

1.1.2 The Sun in X-rays

The multi-wavelength Sun

In X-rays, the Sun looks completely different from what we are used to by observing it with backyard telescopes. Fig. 1.2 shows the changing face of the Sun observed in visible light, Hα, UV and X-rays. The peak of the solar irradiance is in the optical light, which constitutes mostly of continuum emission originating from the photosphere (upper left in Fig. 1.2). The upper right image displays the solar chromosphere in the Hα line of hydrogen at 6562.8 Å. Moving further up in the solar atmosphere, the transition region is visible in emission lines in the EUV (lower left image). Finally, the lower right image shows the solar corona in X-rays.

Emission of the corona

X-ray emission of the Sun originates mostly from the corona, in flares also from lower regions down to the chromosphere. In the quiet Sun, the ob-

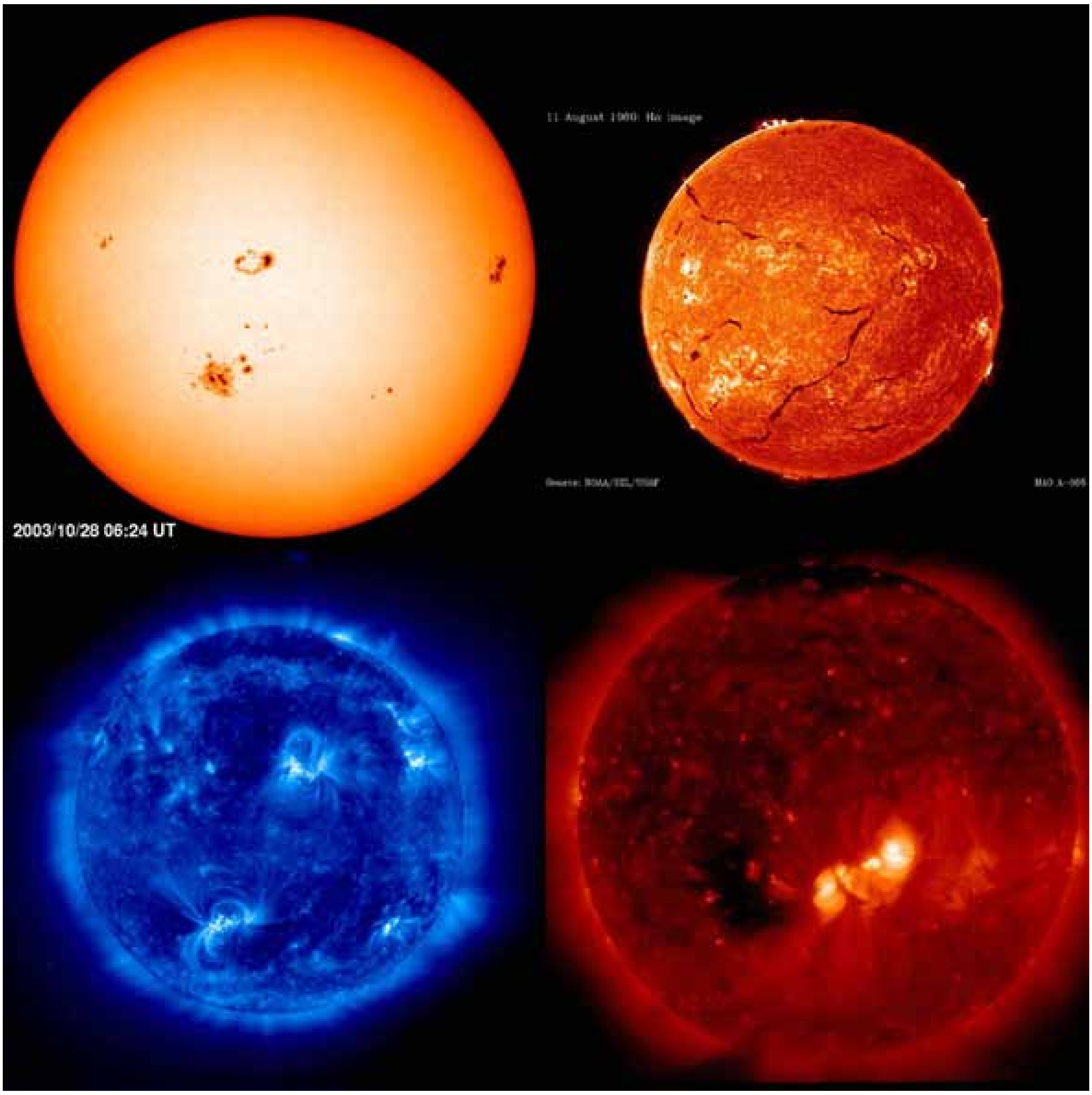

Figure 1.2: The changing face of the Sun. *Top left*: Image of the photosphere in white light with sunspots from SOHO/MDI (ESA & NASA) *Top right*: Image in the Hα emission line (6562.8 Å), displaying the chromosphere (image credit: NOAA/SEL/USAF). Prominences are visible as condensed gas over the limb, dark filaments appear in projection on the disk. *Bottom left*: SOHO/EIT image in the 171 Å wavelength of the EUV spectrum, illustrating the upper transition region at a temperature of about 1 Mio. K. *Bottom right*: Image in X-rays, showing the corona at a temperature of about 2 Mio. K, observed by Hinode (JAXA/NASA/PPARC). (The size of the solar disc is not to scale).

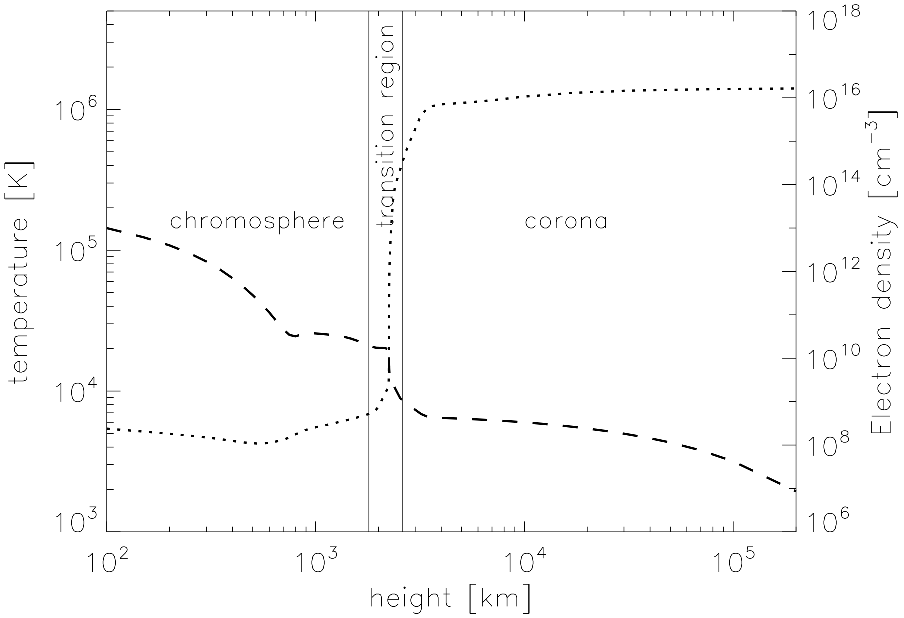

Figure 1.3: Electron temperature (*dotted*) and density (*dashed*) structure of the quiet solar atmosphere (following Benz 2002). The temperature increases by two orders of magnitude from the high layers of the chromosphere to the corona while the electron density decreases considerably.

served emission is hot plasma emission in the form of continuum emission by free electrons, as well as line emission from highly ionized ions. Typical quiet Sun coronal temperatures lie in the range of 1-2 Million degrees. Fig. 1.3 illustrates the electron temperature and electron density structure of the quiet solar atmosphere. In a narrow boundary layer known as transition region, the temperature increases dramatically, while the density decreases with increasing distance from the photosphere. This temperature increase, also known as the *coronal heating problem* is one of the fundamental questions in solar physics and has still not been answered conclusively. An overview of the controversy is given in Aschwanden (2005), reviews can be found in Narain & Ulmschneider (1990) and Narain & Ulmschneider (1996).