Chapter 1

Introduction

This chapter gives a short overview of the principal findings in the study of solar and stellar coronae that are relevant for the subsequent chapters of this thesis. Parts of this chapter are inspired from the literature, and from various reviews and books (Hénoux 1995; Haisch & Schmitt 1996; Golub & Pasaschoff 1997; Hénoux 1998; Schrijver & Zwaan 2000; Güdel 2002).

1.1 General Overview

Although extremely faint in visible light, the outermost region of the solar atmosphere, the corona, can be observed during total eclipses. However, the links between features observed during eclipses (prominences, corona) and the Sun were not established until the second half of the 19th century. They were rather attributed to artifacts introduced by the observational technique, or by the Earth's atmosphere.

The advent of photography (daguerreotypes) and spectroscopy around 1860 drastically changed the scientific approach to the observations of the solar corona. Comparisons of photographs of the 1860 eclipse taken by De la Rue and Secchi at different locations gave proof that prominences were of solar origin, which added weight to the hypothesis that all of the corona was also solar. The use of spectroscopes during eclipses proved highly noteworthy when bright emission lines were discovered. However, it was not until 1939 that Grotrian showed that the coronal lines are emitted by elements such as iron and calcium in very high stages of ionization, implying that the coronal gas is extremely hot (≈ 1 MK).

Although emission lines were first discovered in the visible part of the electromagnetic spectrum, the hot solar corona primarily emits in the extreme ultraviolet and soft X-ray range ($0.1 - 10$ keV), since most of the electronic transitions of highly ionized species decay radiatively in this range. It is therefore the wavelength range of choice to obtain information about the coronal physical processes. However, note that other regions of the solar spectrum, like the radio/microwave or the hard X-ray emission provide complementary information on the high-energy coronal processes as well. Ultraviolet data provide information about the transition region and chromosphere, and thus make a link between the lower part of the atmosphere

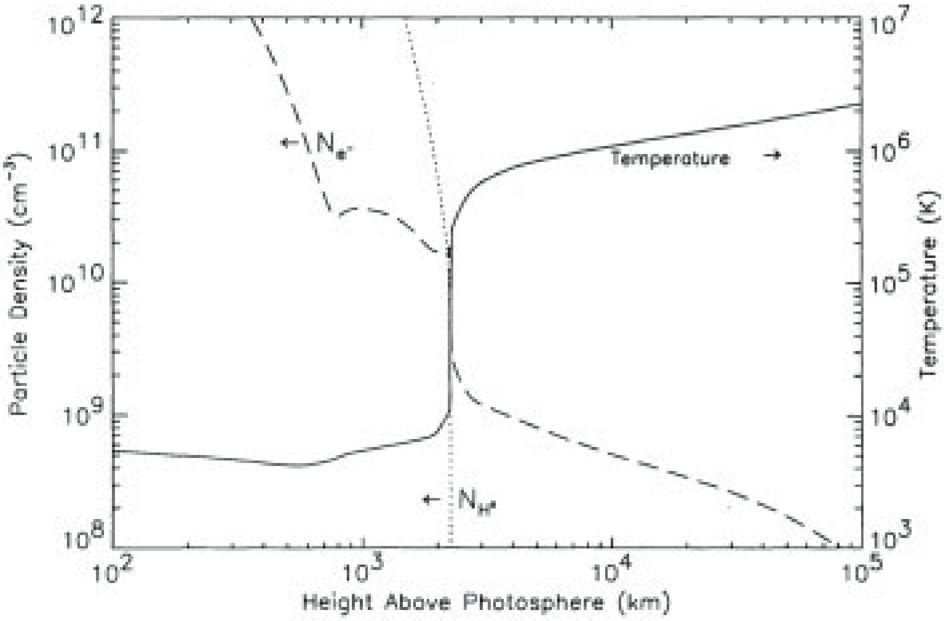

Figure 1.1: *A plane-parallel model of the solar atmosphere showing the temperature (solid) and the electron density (dashed) as a function of height. From Daw, DeLuca, & Golub (1995).*

and the corona. Due to the absorption and scattering of X-ray photons in the Earth's atmosphere, the first detection of X-rays from the solar corona (and from any astrophysical object) had to wait for rocket flight technology (Burnight 1949). The discovery of X-rays from a coronal source other than the Sun, Capella, came a quarter of a century later (Catura, Acton, & Johnson 1975). Numerous satellites (e.g., Skylab, SMM, SOHO, Yohkoh, TRACE) have been dedicated to the observation of the solar corona and have produced excellent high-resolution images and spectra in the soft and hard X-ray ranges. The study of the physical processes in the solar corona is of ongoing interest, for example with the recent launch of the HESSI mission and new missions planned for the near future. In parallel, stellar coronal astrophysics has expanded within the last twenty-five years thanks to detailed investigations of coronal sources with extreme ultraviolet and X-ray satellites (e.g., Einstein, ROSAT, *EUVE*). The launches of the new X-ray observatories, *XMM-Newton* and *Chandra*, at the end of the last century have given a strong impetus to the field of coronal physics.

1.2 The Solar Corona

While the solar surface, i.e., the photosphere, shows an effective temperature of $\approx$ 5800 K, the solar corona displays an extremely high temperature of a few million degrees. This is unexpected, since in the absence of additional heating, the temperature of the atmosphere above the photosphere should drop with height. However, a steep rise in temperature occurs at an altitude of $2000 - 3000$ km above the solar surface. This narrow region is loosely defined as the transition region (TR). Below the TR lies the chromosphere with temperatures of $6000 -$

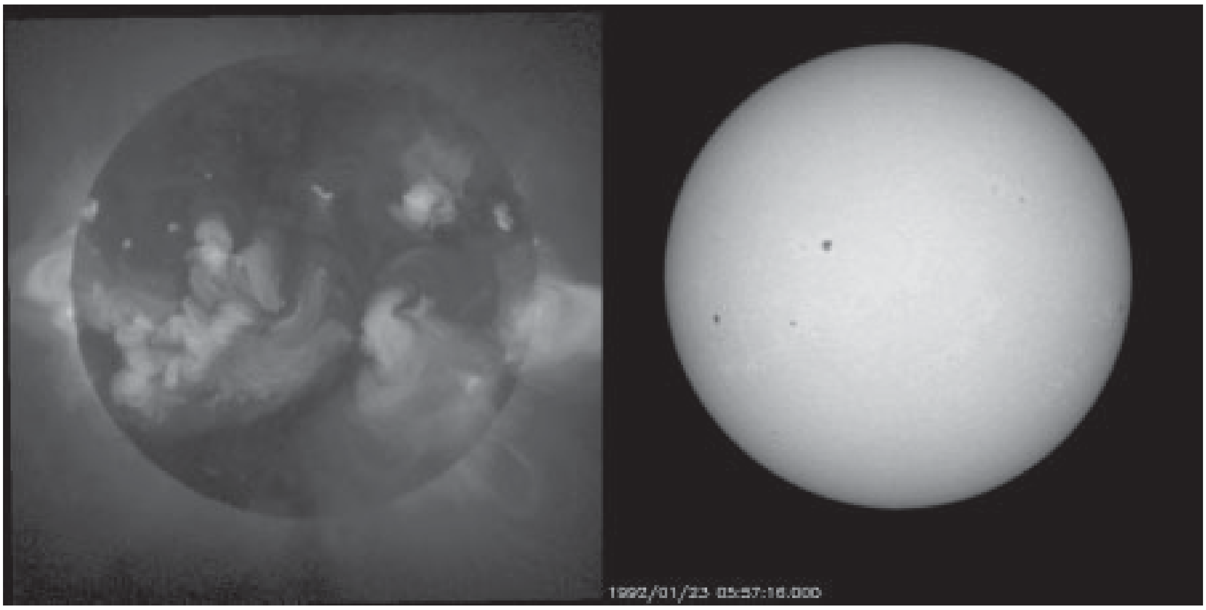

Figure 1.2: *Comparison of the soft X-ray image of the Sun with its simultaneous white light counterpart obtained by Yohkoh, a mission of ISAS, Japan, with NASA cooperation. Coronal holes, X-ray bright points and active regions can be seen in the X-rays. Note the spatial association between sunspots in the visible and coronal active regions in X-rays.*

$10,000$ K (see Fig. 1.1). The mechanisms of coronal heating have been lively debated in solar (and stellar) physics; we address related issues in a subsequent section (§1.4).

1.2.1 A Highly Structured Medium

The solar corona is a highly inhomogeneous medium. X-ray images of the solar corona (Fig. 1.2) reveal the extreme complexity of the coronal structures: bright active regions (associated with underlying photospheric sunspots), quiet regions, and X-ray dark coronal holes (often at the poles). Among others, the Ulysses mission has shown that a steady fast solar wind (750 km s^{-1}) flowing from the solar surface into the interplanetary medium is associated with coronal holes. A slow wind (400 km s^{-1}) is however detected at heliographic latitudes below 20°, with no gradual transition. While certain features persist on long time scales (e.g., coronal holes), the structure of the solar corona changes continuously on time scales of minutes to hours.

A closer look, for example with the high-resolution imaging TRACE satellite, shows the complexity of the coronal structures (Fig. 1.3). The structure of the coronal plasma basically follows the topology of the solar magnetic field: in general, there are closed magnetic fields and field lines that are, from the point of view of coronal physics, open (i.e., they close at very large distances). Coronal holes are generally associated with the latter, while coronal "loops" are with the former. Figure 1.3 shows that the magnetic configuration can be very complex. A loop can be highly stressed, its footpoints can be located in two different active regions, and its

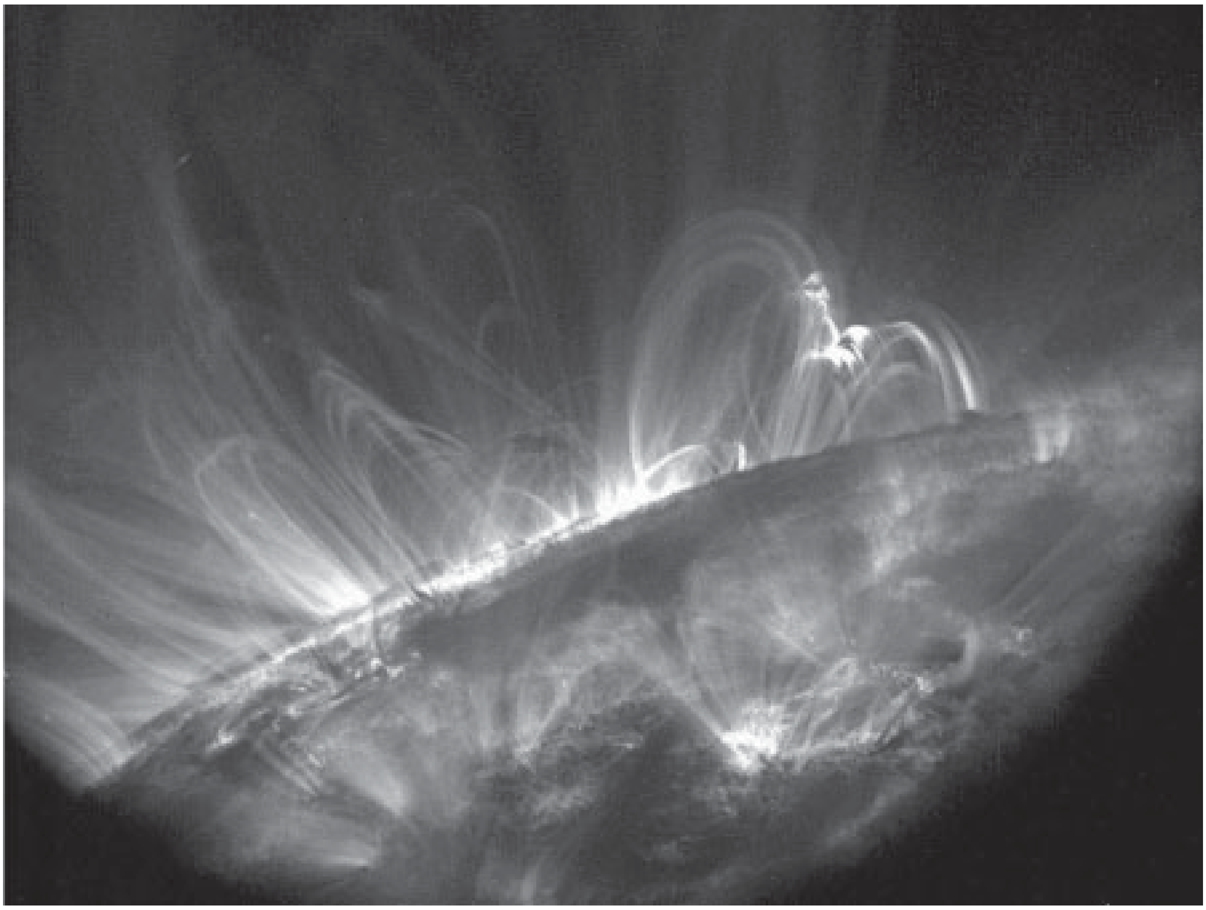

Figure 1.3: *The solar corona and transition region as seen by TRACE on 5 April 2001, around 6:22 UT, in the* Fe IX *line at 171.075 Å ($T_{\rm max} = 1$ MK). The diversity of magnetic structures is evident. Courtesy of the TRACE team.*

configuration can change to a more stable one by reconnection. Recent results from TRACE also showed that coronal loops can oscillate (Schrijver, Aschwanden, & Title 2002).

1.2.2 The Generation of Magnetic Fields – the Solar Dynamo

The presence of a solar magnetic field and of a 22-year cycle of activity (involving a periodic reversal of the magnetic field; the period of the surface activity cycle is however half shorter, i.e., 11 years) are basic properties of the Sun that need to be explained. The solar dynamo theory attempts to explain these properties. Parker (1955) suggested that the coupling of rising material in the convection zone and Coriolis forces should produce non-axisymmetric motion, producing a steady-state amplification of the magnetic field. Either a weak magnetic field is already present, or the motions will generate it. The amplification process needs a natural limit. “Magnetic buoyancy” lifts the magnetic field from the region of its generation up into the atmosphere, and this process is believed to be the limiting process at work in the Sun.