

I

Introduction: solar features and terminology

The Sun serves as the source of inspiration and the touchstone in the study of stellar magnetic activity. The terminology developed in observational solar physics is also used in stellar studies of magnetic activity. Consequently, this first chapter provides a brief illustrated glossary of nonmagnetic and magnetic features, as they are visible on the Sun in various parts of the electromagnetic spectrum. For more illustrations and detailed descriptions, we refer to Bruzek and Durrant (1977), Foukal (1990), Golub and Pasachoff (1997), and Zirin (1988).

The *photosphere* is the deepest layer in the solar atmosphere that is visible in “white light” and in continuum windows in the visible spectrum. Conspicuous features of the photosphere are the *limb darkening* (Fig. 1.1a) and the *granulation* (Fig. 2.12), a time-dependent pattern of bright *granules* surrounded by darker *intergranular lanes*. These nonmagnetic phenomena are discussed in Sections 2.3.1 and 2.5.

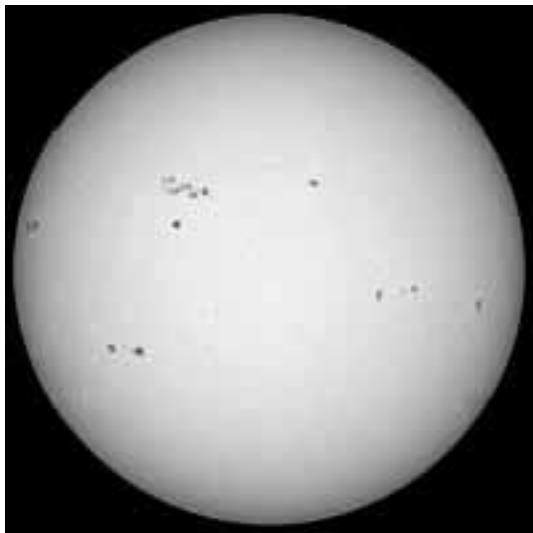
The magnetic structure that stands out in the photosphere comprises dark *sunspots* and bright *faculae* (Figs. 1.1a and 1.2b). A large sunspot consists of a particularly dark *umbra*, which is (maybe only partly) surrounded by a less dark *penumbra*. Small sunspots without a penumbral structure are called *pores*. Photospheric faculae are visible in white light as brighter specks close to the limb.

The *chromosphere* is the intricately structured layer on top of the photosphere; it is transparent in the optical continuum spectrum, but it is optically thick in strong spectral lines. It is seen as a brilliantly purplish-red crescent during the first and the last few seconds of a total solar eclipse, when the moon just covers the photosphere. Its color is dominated by the hydrogen Balmer spectrum in emission. *Spicules* are rapidly changing, spikelike structures in the chromosphere observed beyond the limb (Fig. 4.7 in Bruzek and Durrant, 1977, or Fig. 9-1 in Foukal, 1990).

Chromospheric structure can always be seen, even against the solar disk, by means of monochromatic filters operating in the core of a strong spectral line in the visible spectrum or in a continuum or line window in the ultraviolet (see Figs. 1.1b, 1.1c, 1.2c and 1.3). In particular, filtergrams recorded in the red Balmer line $H\alpha$ display a wealth of structure (Fig. 1.3). *Mottle* is the general term for a (relatively bright or dark) detail in such a monochromatic image. A strongly elongated mottle is usually called a *fibril*.

The photospheric granulation is a convective phenomenon; most other features observed in the photosphere and chromosphere are magnetic in nature. Sunspots, pores, and faculae are threaded by strong magnetic fields, as appears by comparing the magnetograms in Figs. 1.1 and 1.2 to other panels in those figures. On top of the photospheric

2 Introduction: solar features and terminology



1.1 *a*

Fig. 1.1. Four faces of the Sun and a magnetogram, all recorded on 7 December 1991. North is to the top; West is to the right. Panel *a*: solar disk in white light; note the limb darkening. Dark sunspots are visible in the sunspot belt; the bright specks close to the solar limb are the photospheric *faculae* (NSO-Kitt Peak). Panel *b*: solar disk recorded in the Ca II K line core. Only the largest sunspots remain visible; bright *chromospheric faculae* stand out throughout the activity belt, also near the center of the disk. Faculae cluster in *plages*. In addition, bright specks are seen in the *chromospheric network*, which covers the Sun everywhere outside sunspots and plages (NSO-Sacramento Peak). Panel *c*: solar disk recorded in the H α line core. The plages are bright, covering also the sunspots, except the largest. The dark ribbons are called *filaments* (Observatoire de Paris-Meudon). Panel *d*: the solar *corona* recorded in soft X-rays. The bright *coronal condensations* cover the active regions consisting of sunspot groups and faculae. Note the intricate structure, with loops. Panel *e*: magnetogram showing the longitudinal (line-of-sight) component of the magnetic field in the photosphere; light gray to white patches indicate positive (northern) polarity, and dark gray to black ones represent negative (southern) polarity. Note that the longitudinal magnetic signal in plages and network decreases toward the limb (NSO-Kitt Peak).

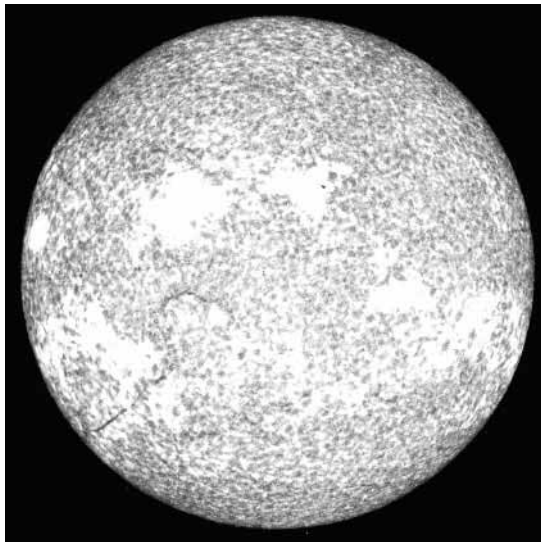
faculae are the *chromospheric faculae*, which are well visible as bright fine mottles in filtergrams obtained in the Ca II H or K line (Fig. 1.1*b*) and in the ultraviolet continuum around 1,600 Å (Fig. 1.2*c*). Whereas the faculae in “white light” are hard to see near the center of the disk,* the chromospheric faculae stand out all over the disk.

The magnetic features are often found in specific configurations, such as *active regions*. At its maximum development, a large active region contains a group of sunspots and faculae. The faculae are arranged in *plages* and in an irregular network, called the *enhanced network*. The term *plage* indicates a tightly knit, coherent distribution of faculae; the term is inspired by the appearance in filtergrams recorded in one of the line cores of the Ca II resonance lines (see Figs. 1.1*b* and 1.3*a*). Enhanced network stands out in

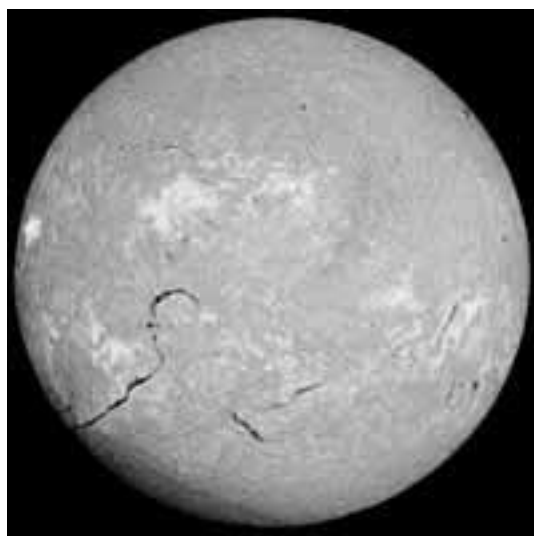
* Some of the drawings in Father Schreiner’s (1630) book show faculae near disk center.

Introduction: solar features and terminology

3



1.1 *b*

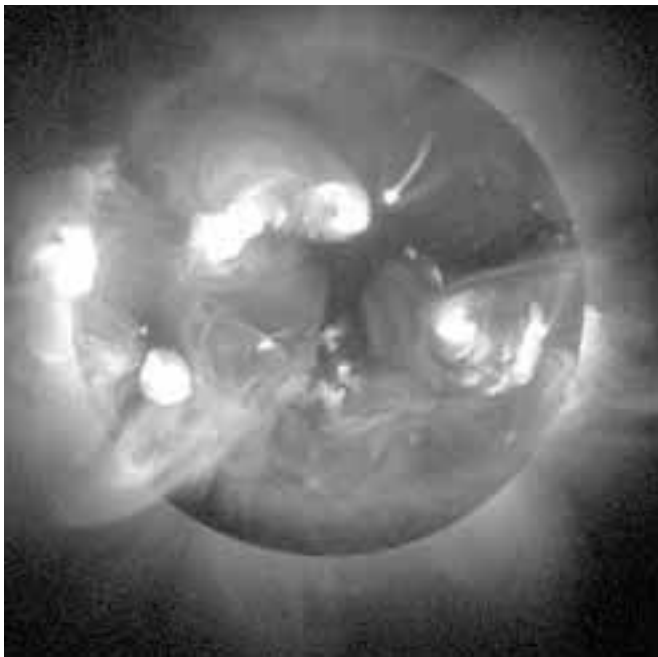


1.1 *c*

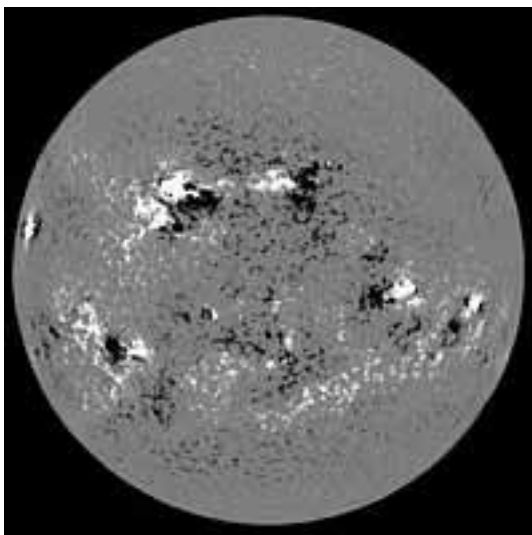
Figs. 1.2*b* and 1.2*c*. All active regions, except the smallest, contain (a group of) sunspots or pores during the first part of their evolution.

Active regions with sunspots are exclusively found in the *sunspot belts* on either side of the solar equator, up to latitudes of $\sim 35^\circ$; the panels in Fig. 1.1 show several large active regions. In many young active regions, the two magnetic polarities are found in a nearly E–W bipolar arrangement, as indicated by the magnetogram of Fig. 1.1*e*, and better in the orientations of the sunspot groups in Fig. 1.1*a*. Note that on the northern solar hemisphere in Fig. 1.1*e* the western parts of the active regions tend to be of negative

4 *Introduction: solar features and terminology*



1.1 *d*



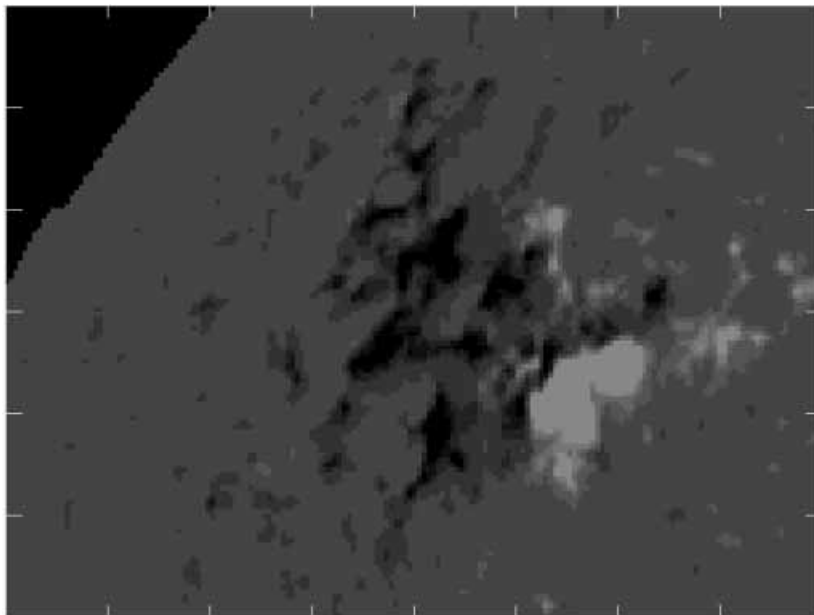
1.1 *e*

polarity, whereas on the southern hemisphere the western parts are of positive polarity. This polarity rule, discovered by G. E. Hale, is discussed in Section 6.1.

Since many active regions emerge close to or even within existing active regions or their remnants, the polarities may get distributed in a more irregular pattern than a simple bipolar arrangement. Such a region is called a complex active region, or an *activity complex*. Figure 1.2 portrays a mildly complex active region.

Introduction: solar features and terminology

5



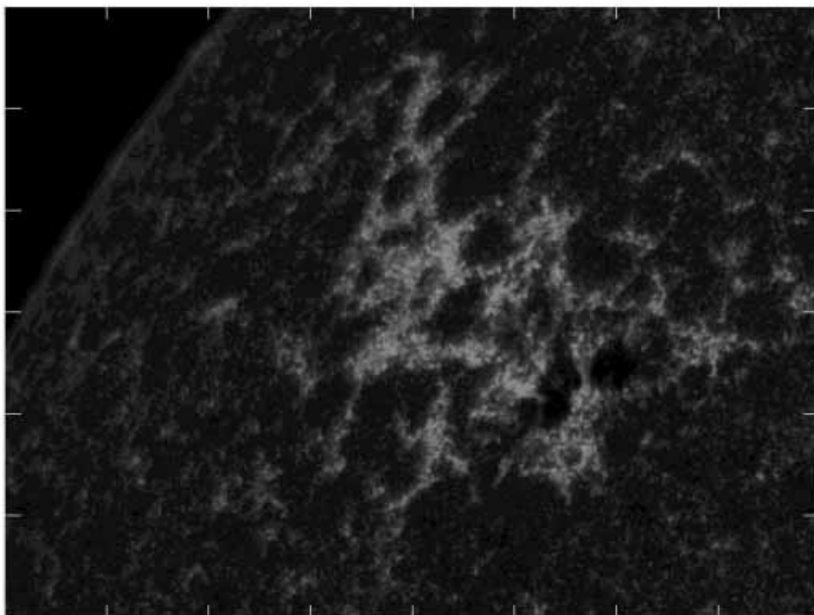
1.2 *a*



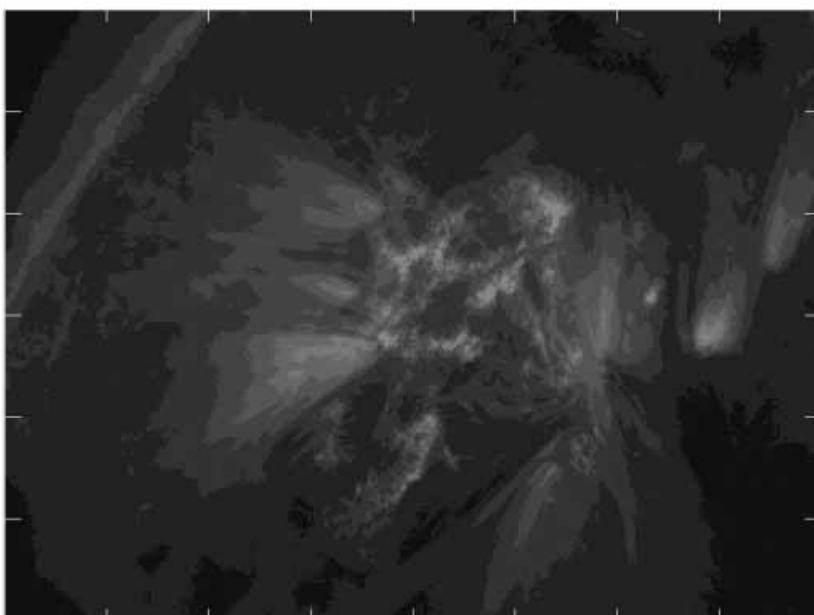
1.2 *b*

Fig. 1.1. Complex active region AR 8,227 observed on 28 May 1998 around 12 UT in various spectral windows. Panels: *a*, magnetogram (NSO-Kitt Peak); *b*, in white light (*TRACE*); *c*, in a 100-Å band centered at $\sim 1,550$ Å, showing the continuum emission from the high photosphere and C IV transition-region emission (*TRACE*); *d*, at 171 Å, dominated by spectral lines of Fe IX and Fe X, with a peak sensitivity at $T \approx 1$ MK (*TRACE*).

6 *Introduction: solar features and terminology*



1.2 c



1.2 d

Introduction: solar features and terminology

7

When a large active region decays, usually first the sunspots disappear, and then the plages crumble away to form enhanced network. One or two stretches of enhanced network may survive the active region as a readily recognizable bipolar configuration. Stretches of enhanced network originating from several active regions may combine into one large strip consisting of patches of largely one dominant polarity, a so-called unipolar region. On the southern hemisphere of Fig. 1.1*e*, one such strip of enhanced network of positive (white) polarity stands out. Enhanced network is a conspicuous configuration on the solar disk when activity is high during the sunspot cycle.

Outside active regions and enhanced network, we find a *quiet network* that is best visible as a loose network of small, bright mottles in Ca II K filtergrams and in the UV continuum. Surrounding areas of enhanced network and plage in the active complex, the quiet network is indicated by tiny, bright mottles; see Fig. 1.2*c*. Quiet network is also visible on high-resolution magnetograms as irregular distributions of tiny patches of magnetic flux of mixed polarities. This mixed-polarity quiet network is the configuration that covers the solar disk everywhere outside active regions and their enhanced-network remnants; during years of minimum solar activity most of the solar disk is dusted with it. The areas between the network patches are virtually free of strong magnetic field in the photosphere; these areas are often referred to as internetwork cells. Note that in large parts of the quiet network, the patches are so widely scattered that a system of cells cannot be drawn unambiguously.

The distinctions between plages, enhanced network, and quiet network are not sharp. Sometimes the term *plagette* is used to indicate a relatively large network patch or a cluster of faculae that is too small to be called plage.

Bright chromospheric mottles in the quiet network are usually smaller than faculae in active regions and mottles in enhanced network, but otherwise they appear similar. Historically, the term *facula* has been reserved for bright mottles within active regions; we call the bright mottles outside active regions *network patches*. (We prefer the term patch over point or element, because at the highest angular resolution these patches and faculae show a fine structure.)

The comparison between the magnetograms and the photospheric and chromospheric images in Figs. 1.1 and 1.1 shows that near the center of the solar disk there is an unequivocal relation between sites of strong, vertical magnetic field and sunspots, faculae, and network patches. As a consequence, the adjectives magnetic and chromospheric are used interchangeably in combination with faculae, plages, and network.

In most of the magnetic features, the magnetic field is nearly vertical at the photospheric level, which is one of the reasons for the sharp drop in the line-of-sight magnetic signal in plages and network toward the solar limb in Fig. 1.1*e*. Markedly inclined photospheric fields are found within tight bipoles and in sunspot penumbrae.

Filtergrams obtained in the core of H α are much more complex than those in the Ca II H and K lines (see Fig. 1.3, and Zirin's 1988 book, which is full of them). In addition to plages and plagettes consisting of bright mottles, they show a profusion of elongated dark fibrils. These fibrils appear to be directed along inclined magnetic field lines in the upper chromosphere (Section 8.1); they are rooted in the edges of plages and in the network patches. The fibrils stand out particularly well in filtergrams obtained at $\sim 0.5 \text{ \AA}$ from the line core (see Fig. 1.3*b*).

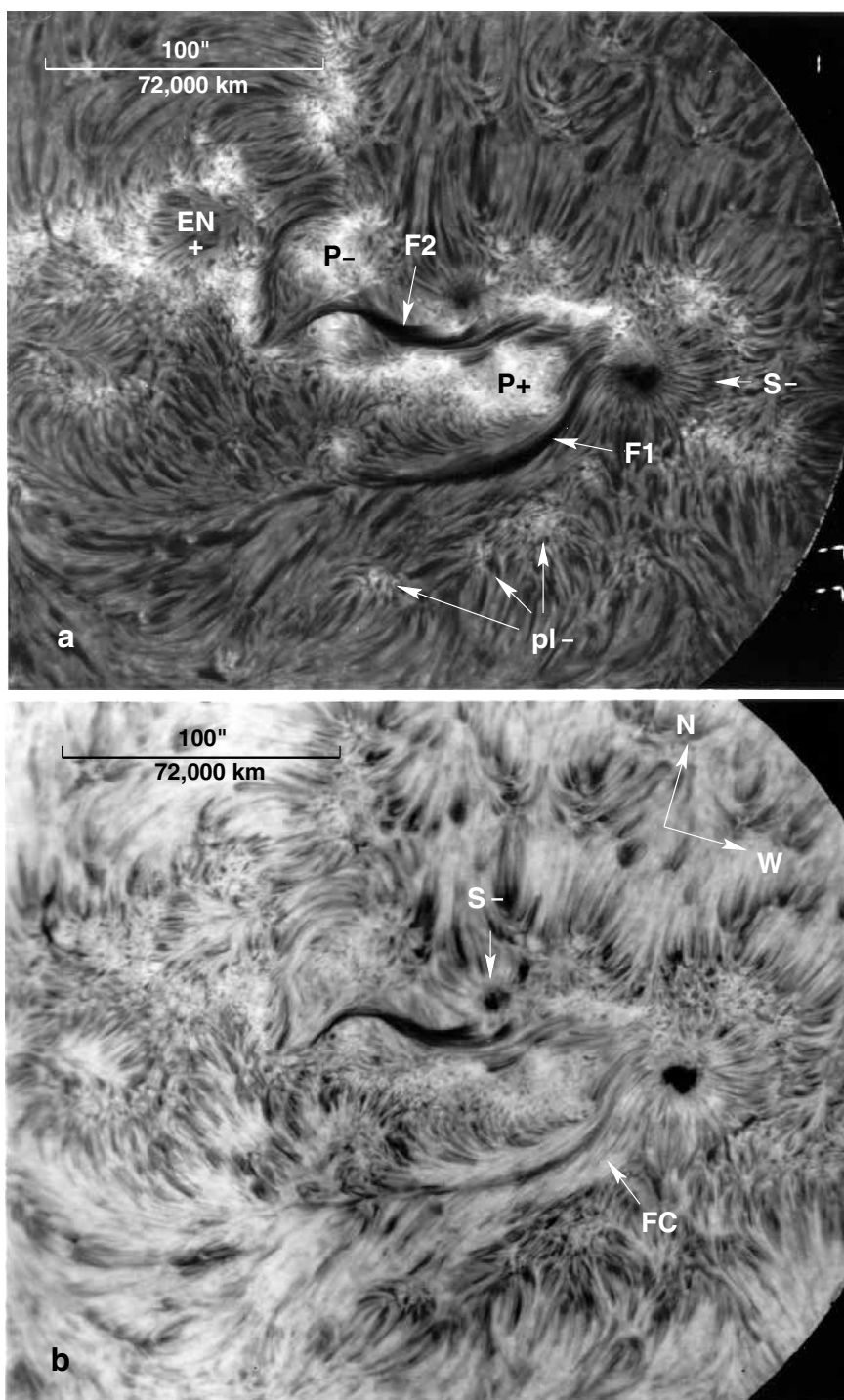


Fig. 1.3. Nearly simultaneous H α filtergrams of active complex McMath 14,726 on 18 April 1977, observed in the line core (panel *a*) and at $\Delta\lambda = +0.65 \text{ \AA}$ in the red wing (panel *b*). The letter symbols indicate the following: S, sunspot; P, plage; pl, plagette; F, filament; FC, filament channel; EN, enhanced network cell. Signs are appended to indicate the magnetic polarities. Fibrils are prominent in both panels. Exceptionally long and well-ordered fibrils are found in the northwestern quadrants. Several features are discussed in Sections 8.1 and 8.2. The chirality of filament F1 is sinistral (figure from the archive of the Ottawa River Solar Observatory, National Research Council of Canada, courtesy of V. Gaizauskas.)

Introduction: solar features and terminology

9

The longest dark structures visible in the core of the $H\alpha$ line are the *filaments* (Figs. 1.1c and 1.3). Many filaments are found at borders of active regions and within active complexes, but there are also filaments outside the activity belts, at higher latitudes. Most filaments differ from fibrils by their length and often also by their detailed structure. Small filaments can be distinguished from fibrils by their reduced contrast at distances $|\Delta\lambda| \gtrsim 0.5 \text{ \AA}$ from the line core. Large filaments are visible outside the solar limb as *prominences* that are bright against a dark background.

The *corona* is the outermost part of the Sun, which is seen during a total eclipse as a pearly white, finely structured halo, locally extending to several solar radii beyond the photospheric limb; see Figs. 8.4 and 8.11, Fig. 1.2 in Golub and Pasachoff (1997), or Fig. 9-10 in Foukal (1990). The coronal plasma is extremely hot ($T \sim 1 \times 10^6 - 5 \times 10^6 \text{ K}$) and tenuous. The radiation of the white-light corona consists of photospheric light, scattered by electrons in the corona and by interplanetary dust particles; the brightness of the inner corona is only $\sim 10^{-6}$ of the photospheric brightness. The thermal radiation of the corona is observed in soft X-rays, in spectral lines in the ultraviolet and optical spectrum, and in radio waves. The corona is optically thin throughout the electromagnetic spectrum, except in radio waves and a few resonance lines in the extreme ultraviolet and in soft X-rays.

The coronal structure in front of the photospheric disk can be observed from satellites in the EUV and in X-rays; see Figs. 1.1d and 1.2d. In these wavelength bands, the coronal plasma, however optically thin, outshines the much cooler underlying photosphere. The features depend on the magnetic field in the underlying photosphere. The corona is particularly bright in “coronal condensations” immediately above all active regions in the photosphere and chromosphere. Coronal loops trace magnetic field lines connecting opposite polarities in the photosphere. Note that in Fig. 1.1d there are also long, somewhat fainter, loops that connect magnetic poles in different active regions. The finest coronal structure is displayed in Fig. 1.2d, where the passband reveals radiation from bottom parts of loops with $T \lesssim 1 \times 10^6 \text{ K}$, without contamination by radiation from hotter loops with $T \gtrsim 2 \times 10^6 \text{ K}$.

Coronal holes stand out as regions that emit very little radiation; these have been identified as regions where the magnetic field is open to interstellar space. Usually large coronal holes are found over the polar caps; occasionally smaller coronal holes are observed at low latitudes.

2

Stellar structure

This chapter deals with the aspects of stellar structure and evolution that are thought to be independent of the presence of magnetic fields. In this classical approach to global stellar structure, the effects of stellar rotation are also ignored. Rather than summarize the theory of stellar structure, we concentrate on features that turn out to be important in understanding atmospheric structure and magnetic activity in Sun-like stars, that is, stars with convective envelopes. For more comprehensive introductions to stellar structure we refer to Chapter 4 in Unsöld and Baschek (1991), and to Böhm-Vitense (1989a, 1989b, 1989c).

We present a brief synopsis of the transfer of electromagnetic radiation in order to indicate its role in the structuring of stellar atmospheres and to sketch the possibilities and limitations of spectroscopic diagnostics, including Zeeman diagnostics of magnetic fields.

In addition, in this chapter we summarize the convective and purely hydrodynamic wave processes in stellar envelopes and atmospheres. In this framework, we also discuss the basal energy deposition in outer atmospheres that is independent of the strong magnetic fields.

2.1 Global stellar structure

2.1.1 Stellar time scales

Stars are held together by gravity, which is balanced by gas pressure. Their quasi-steady state follows from the comparison of some characteristic time scales.

The *time scale of free fall* $\hat{t}_{\text{ff}}$ is the time scale for stellar collapse if there were no pressure gradients opposing gravity. Then the only acceleration is by gravity: $d^2r/dt^2 = -GM/r^2$, where r is the radial distance to the stellar center, G is the gravitational constant, and M and R are the stellar mass and radius, respectively. This leads to the order-of-magnitude estimate:

$$\hat{t}_{\text{ff}} \approx \left(\frac{R^3}{GM} \right)^{1/2} = 1,600 \left(\frac{M}{M_{\odot}} \right)^{-1/2} \left(\frac{R}{R_{\odot}} \right)^{3/2} \text{ (s)}, \quad (2.1)$$

where $M_{\odot}$ and $R_{\odot}$ are the solar mass and radius, respectively.

For a star virtually in hydrostatic equilibrium, local departures from equilibrium are restored at the speed of sound:

$$c_s = [(\gamma p)/\rho]^{1/2}, \quad (2.2)$$