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The Sun among the stars

Our Sun is a typical, middle-aged star, but it occupies a special place in astronomy as the only star that we can observe in great detail. Conversely, it is only by studying other stars with different properties, whether of age, mass or angular momentum, that we can fully explain the behaviour of the Sun. This book is concerned with dark spots on the surfaces of the Sun and other stars, which result from the interplay between magnetic fields and convection. In this opening chapter we provide a brief introduction to the properties of these spots, a summary of the important overall properties of the Sun and other stars, and an overview of the topics that will be covered in the remainder of the book.

1.1 Sunspots and solar magnetic activity

In this section we introduce a variety of features and phenomena associated with sunspots and solar activity, all of which will be discussed in greater detail in later chapters.

In images of the full solar disc, such as that shown in Figure 1.1, sunspots appear as dark patches at low latitudes. The fact that sunspots are associated with strong magnetic fields emerging through the solar surface is readily apparent in the accompanying *magnetogram* in Figure 1.1, which shows the strength and polarity of the longitudinal (line-of-sight) magnetic field.

In a close-up image, such as the one in Figure 1.2, a typical sunspot is seen to consist of a dark central region called the *umbra* surrounded by a less dark, annular region called the *penumbra*. Some sunspots are remarkably circular and axisymmetric (favourites of theoreticians), while others have very irregular shapes with perhaps only partial penumbrae. There are also smaller dark features known as *pores* that are essentially naked umbrae, or spots without penumbrae. Examples of both sunspots and pores can be seen in Figure 1.2. Also evident in this image is the pattern of *granulation* in regions outside of sunspots, caused by thermal convection just below the solar surface. This pattern consists of bright *granules* corresponding to hot, rising plumes of gas, surrounded by dark lanes corresponding to cooler downflows. A typical bright granule is about 700 km, or $1''$, across.[1]

The most conspicuous feature of a sunspot is, of course, its darkness relative to the surrounding photosphere. In an absolute sense, a sunspot is not so dark; indeed, if it were placed alone in space at the same distance from us as the Sun, it would shine about as brightly as the full Moon, a fact already understood by Galileo. A sunspot appears dark on the solar

[1] As viewed from the Earth at the mean Earth–Sun distance, an angle of one arcsecond ($1''$) is subtended by a distance of 726 km on the surface of the Sun at the centre of the solar disc.

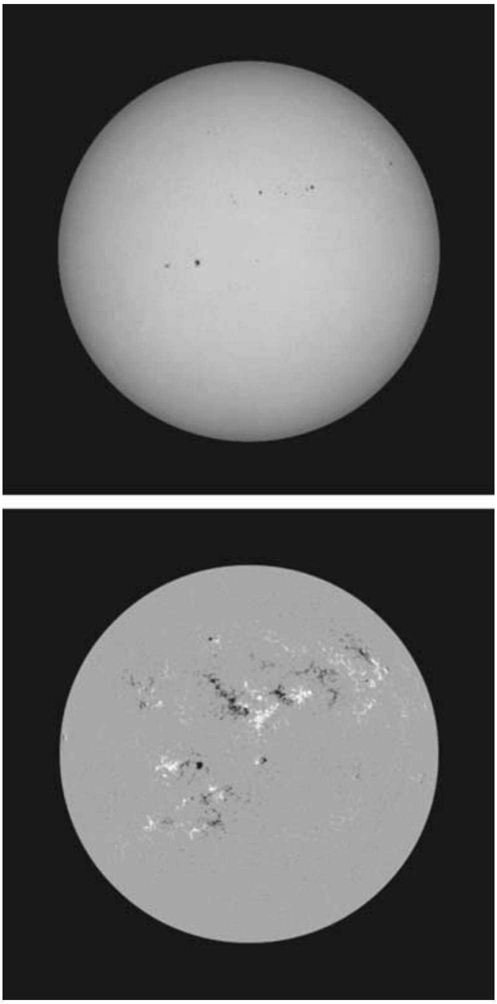

Fig. 1.1. SOHO images of the full solar disc in white light (above) and as a magnetogram (below) on 8 February 2001. In each image, North is upward and East and West are to the left and right, respectively, according to the usual convention. (Courtesy of Lockheed-Martin Solar and Astrophysics Laboratory.)

disc because it is relatively cooler than its surroundings, and we understand that the reduced temperature is due to the inhibiting effect of the spot's strong magnetic field on the vertical convective transport of heat just below the solar surface.

Sunspots come in a wide range of sizes. The largest have diameters of 60 000 km or more and are visible to the naked eye. At the other end of the scale are the pores, which have diameters typically in the range 1500–3500 km but can be as small as a single granule (about 700 km) or as large as a small sunspot (7000 km). Indeed, the largest pores are bigger than the smallest sunspots, a fact of some importance when we come to consider the formation and maintenance of the penumbra.

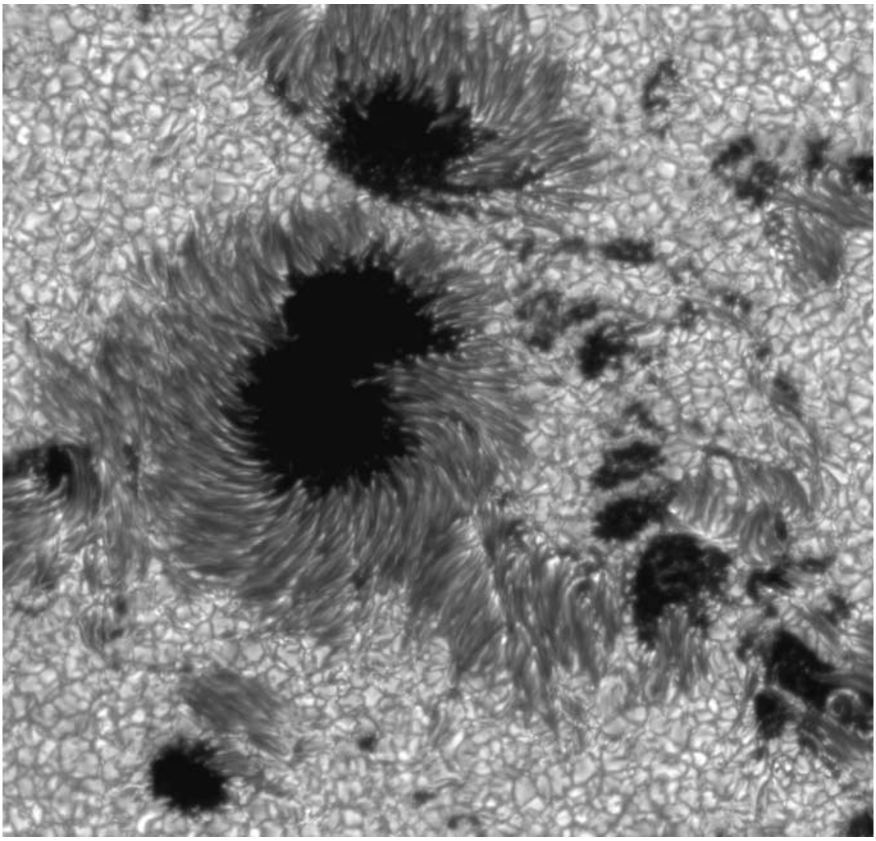

Fig. 1.2. High-resolution G-band image, obtained with the Swedish Solar Telescope, showing an active region with sunspots and pores. Penumbral filaments are clearly visible, as is the surrounding pattern of granular-scale convection. (Courtesy of the Royal Swedish Academy of Sciences.)

Within a sunspot there is a good deal of fine structure that becomes evident with higher resolution and suitable exposure times. The penumbra displays a characteristic pattern of elongated, bright and dark radial *penumbral filaments*, while the dark umbra contains a number of small, bright features known as *umbral dots* (which are not very evident in Fig. 1.2 because the umbra is under-exposed). This fine structure in the intensity of light emerging from a spot is a consequence of the pattern of thermal convection as influenced by the spot's magnetic field (*magnetoconvection*).

A sunspot marks a patch of the solar surface through which a close-packed bundle of nearly vertical magnetic flux (a magnetic flux tube) emerges from the solar interior. The magnetic field strength in the centre of a sunspot is typically about 2800 G (or 0.28 T) and can be as high as 3500 G or more. The magnetic field exerts a force on the solar plasma, consisting in general of a tension force along the field lines and an isotropic pressure. The total pressure, gas plus magnetic, within the spot must be in balance with the gas pressure in the field-free surroundings. As a consequence, the spot's magnetic flux tube must expand (in cross-section) rapidly with height above the solar surface, thus reducing its magnetic pressure, in order to be in pressure balance with the external atmosphere, in which the gas pressure is decreasing rapidly (nearly exponentially) with height.

In addition to dark sunspots and pores, there are also localized patches of excess brightness on the solar surface, known as *faculae*, which are also sites of strong emerging magnetic field. (Faculae are visible in the full-disc image in Fig. 1.1.) There are several other visible manifestations of the Sun's magnetic field, including enhanced emission from the upper layers of the solar atmosphere and transient events such as flares, surges and radio bursts. These phenomena, known collectively as *solar magnetic activity* (or simply solar activity), are not distributed uniformly across the solar surface, but instead are concentrated into *active regions* containing one or more sunspots, pores and surrounding faculae. Figure 1.3 shows

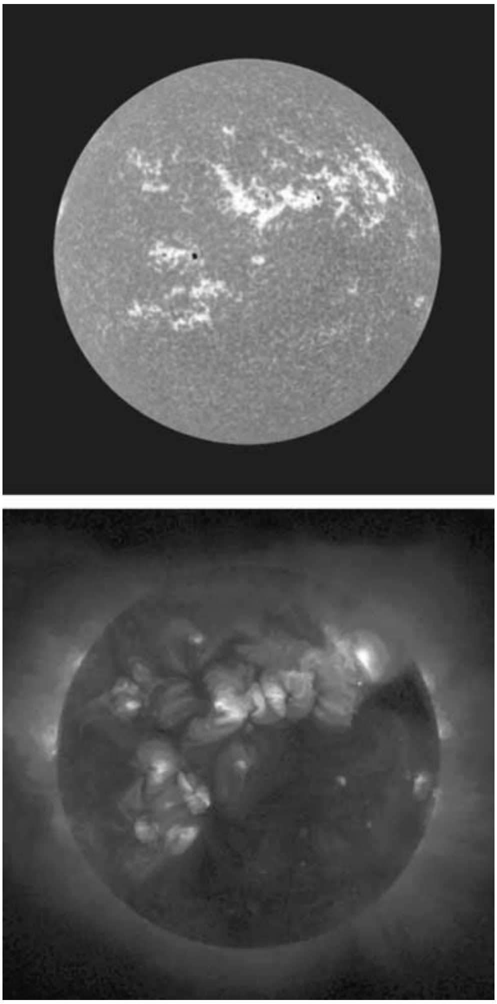

Fig. 1.3. Images of the full solar disc in Ca II K emission (above, from Big Bear Solar Observatory) and in coronal X-ray emission (below, from Yohkoh), again on 8 February 2001. (Courtesy of Lockheed-Martin Solar and Astrophysics Laboratory.)

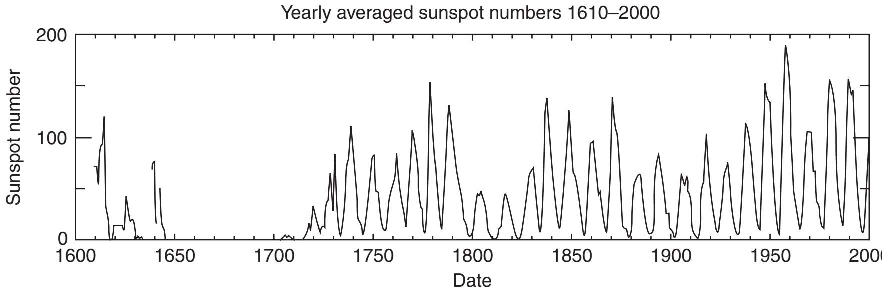

Fig. 1.4. Cyclic solar activity from AD 1610 to 2000, as shown by annual values of the group sunspot number. Note the interval of inactivity in the seventeenth century (the Maunder Minimum). (Courtesy of D. H. Hathaway.)

full disc images of Ca II emission (from the chromosphere) and X-ray emission (from the corona) in which active regions are clearly identifiable.

Solar activity is also not uniformly distributed in time: it varies in a nearly cyclic fashion with a period of about 11 years. This behaviour is readily apparent in the record of the number of sunspots appearing on the solar disc, as shown in Figure 1.4. Here one can see a somewhat irregular cyclic variation in the number of sunspots, with an average period between maxima of about 11 years, and a longer-term modulation of this cyclic variation. Of particular interest is the period from about 1645 to 1715 during which there were very few sunspots (the so-called *Maunder Minimum*).

The sunspot cycle has a period of about 11 years, but the magnetic polarity arrangement of the spots reverses in each successive cycle, indicating a signed magnetic cycle with a period of about 22 years. It is generally understood that the Sun's magnetic field and its cyclic behaviour are generated by a fluid *dynamo* acting in the solar interior through the interaction between the Sun's internal differential rotation and turbulent convection.

1.2 The Sun as a star

In this section we first describe the overall properties of the Sun and the structure of its interior and atmosphere, and then go on to summarize the overall properties of other stars to set the stage for our discussions of starspots and stellar activity.

1.2.1 Solar structure

Table 1.1 provides a list of important properties of the Sun that will prove useful in our discussions of sunspots and solar magnetism. For a clear discussion of how the values of these various quantities are determined, see the book by Stix (2002).

The radial structure of the Sun is depicted schematically in Figure 1.5. The energy generated by nuclear reactions in the *core* (where the temperature is of order 10^7 K) is carried radially outward by radiation across the *radiative zone* extending out to roughly 0.7 $R_\odot$, where the temperature of the solar plasma has decreased to the point where the increased opacity no longer permits the energy flux to be carried by radiation alone and thermal convection sets in. The energy is then carried outward almost exclusively by convection across the *convection zone* extending up to the solar surface. The relatively sharp visible surface of

Table 1.1 *Properties of the Sun*

Age	4.5×10^9 yr
Mass	$M_\odot = 1.99 \times 10^{30}$ kg
Radius	$R_\odot = 6.96 \times 10^8$ m = 696 000 km
Luminosity	$L_\odot = 3.84 \times 10^{26}$ W = 3.84×10^{33} erg s^{-1}
Effective temperature	$T_{\mathrm{eff}} = 5785$ K
Spectral type	G2 V
Mean density	1.4×10^3 kg m^{-3}
Surface gravity	$g_\odot = 274$ m s^{-2}
Rotation period (equatorial)	26 days
Distance from Earth	1 AU = 1.50×10^{11} m = 215 $R_\odot$

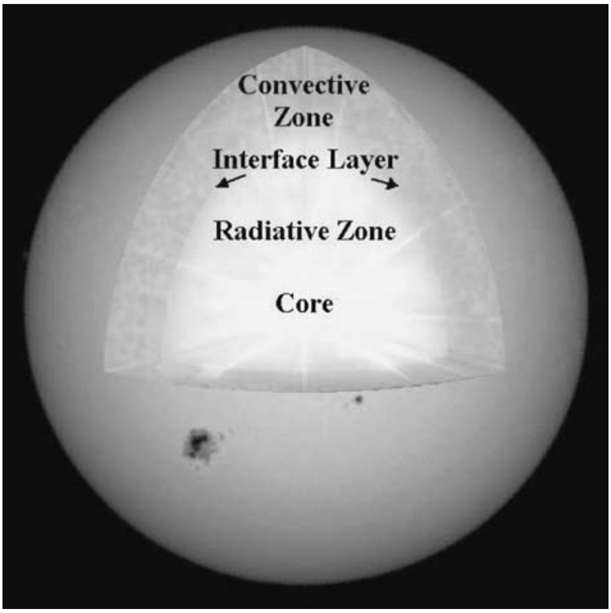

Fig. 1.5. Cutaway image of the Sun's internal structure, showing the photosphere (with sunspots), the convective zone beneath it, the inner radiative zone and the central core, where energy is generated by thermonuclear reactions. The tachocline is located at the interface between the radiative and convective zones. (Courtesy of D. H. Hathaway.)

the Sun occurs where the mean free path of photons increases abruptly and radiation is permitted to escape unimpeded into space; this transition takes place across a thin layer known as the *photosphere*, which is only a few hundred kilometres thick. In this layer, and higher layers of the solar atmosphere, a geometric height is determined from a measured *optical depth* τ_λ: a layer of optical depth $\tau_\lambda = 1$ reduces the intensity of radiation at wavelength λ by a factor of e^{-1}, and each further unit of τ_λ reduces the intensity by a further factor of e^{-1}. The most commonly used optical depth is τ_{500}, for radiation in a continuum window at wavelength 500 nm near the centre of the visible range.

At the base of the photosphere the temperature is about 6000 K, close to the Sun's *effective temperature* $T_{\text{eff}} = 5785$ K based on its luminosity. The temperature reaches a minimum value of about 4200 K in the upper photosphere and then begins climbing again, reaching some 10 000 K or so in the *chromosphere*, named for its coloured appearance during a solar eclipse. Above the chromosphere, the temperature climbs steeply across a relatively thin *transition region* and reaches values of 2×10^6 K or more in the corona. The temperature then decreases in the outer corona, which expands and flows outward into space as the *solar wind*.

Direct observations are limited to the surface and atmosphere of the Sun (containing only $10^{-10}\,M_\odot$), while its magnetic fields are generated in the solar interior. Fortunately, this interior is accessible to *helioseismology*: the frequencies and horizontal wavenumbers of acoustic *p*-modes (with typical periods around 5 minutes) can be measured with great accuracy and used to establish the internal structure of the Sun with previously unattainable precision. The most remarkable achievement has been the determination of the Sun's internal rotation profile. It has long been known that equatorial regions rotate faster than polar regions at the surface, but helioseismology has shown that this differential rotation persists throughout the convection zone. There is then an exceedingly abrupt transition, across a thin layer – the *tachocline* (less than 0.04 $R_\odot$ thick) – to an almost uniformly rotating radiative interior (Thompson *et al.* 2003).

1.2.2 Properties and classification of stars

Although the most fundamental property of a star is its total mass, stars are usually classified according to their directly observable properties of luminosity and colour, or luminosity and surface temperature (which can be inferred from the colour). This classification is most often displayed in a *Hertzsprung–Russell (H–R) diagram*, in which the absolute magnitude (or the logarithm of the total luminosity) is plotted against the logarithm of the surface temperature (by tradition, decreasing to the right). When a large sample of stars is plotted in such a way, as in Figure 1.6, it is evident that most of the stars lie along a relatively narrow

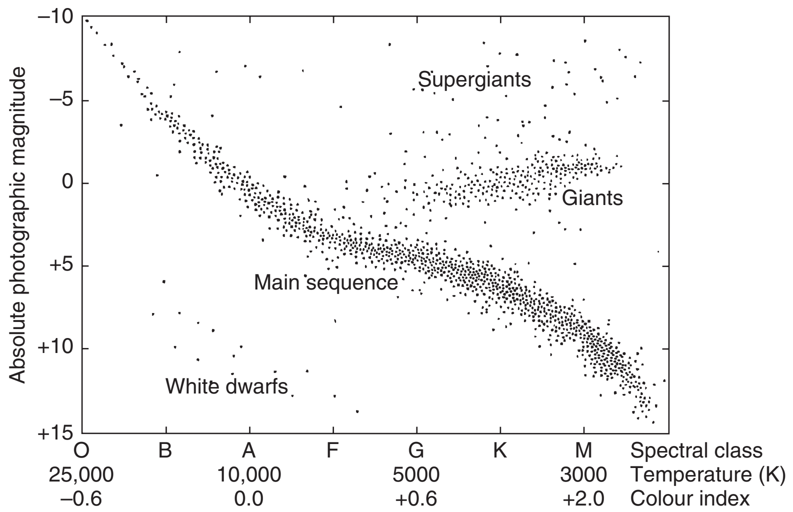

Fig. 1.6. The Hertzsprung–Russell diagram for a sample of stars of known distance. (From Abell 1964.)

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band known as the *main sequence*. From the point of view of stellar evolution, the main sequence represents a long, intermediate stage in which stars spend most of their lifetime.

The Harvard classification scheme of stars into *spectral types* O, B, A, F, G, K, M, R and S represents a sequence of decreasing mass and decreasing surface temperature, and generally increasing complexity in their spectra. Each letter class has ten subdivisions (e.g. G0 through G9) in the order of decreasing surface temperature. Stars are also divided into *luminosity classes* according to their size, or phase of evolution, as follows: I for supergiants, II for bright giants, III for giants, IV for subgiants, V for main-sequence (or dwarf) stars, and VI for subdwarfs. The Sun, for example, is a G2 V star, and the star SU Aurigae, of class G2 III, is a giant star with a solar-like spectrum.

The *bolometric* (or total) *luminosity* L of a star is its total rate of energy output, integrated over all wavelengths; it is often expressed in units of the solar luminosity $L_\odot = 3.84 \times 10^{33}\,\mathrm{erg\,s^{-1}}$. Because the Earth's atmosphere is opaque at many wavelengths, L is in general difficult to determine, and instead the luminosity is often measured within certain wavelength bands, such as the V (visual) band centred on wavelength $\lambda = 555\,\mathrm{nm}$, the B (blue) band centred on $\lambda = 435\,\mathrm{nm}$, and the U (ultraviolet) band centred on $\lambda = 350\,\mathrm{nm}$, each band having relative width $\Delta\lambda/\lambda = 0.2$. The luminosity L in each band is often expressed on a logarithmic scale in terms of the *absolute magnitude* M in that band, defined by

$$M \equiv -2.5 \log_{10} L + C, \tag{1.1}$$

where C is a constant that is different for each wavelength band. For the B and V bands the constants are chosen so that the Sun has magnitudes $M_{B\odot} = 5.48$ and $M_{V\odot} = 4.83$. The magnitudes M_B and M_V are usually denoted simply as B and V.

The *colour* of a star is measured by the ratio of its luminosity in two wavelength bands, most often by L_V/L_B or equivalently by $B - V$. To the extent that a star's spectrum matches that of a black body, the colour $B - V$ is a measure of the surface temperature of the star. A more precise measure of a star's surface temperature is given by its *effective temperature* T_{eff}, defined as the temperature of a spherical black body having the same radius and bolometric luminosity as the star. Thus, according to the Stefan–Boltzmann law, T_{eff} is given in terms of a star's bolometric luminosity L by the relation

$$L = 4\pi R^2 \sigma {T_{\mathrm{eff}}}^4, \tag{1.2}$$

where R is the star's radius and $\sigma = 5.67 \times 10^{-5}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,K^{-4}}$.

From a theoretical viewpoint, the fundamental properties of a star that determine its position on the H–R diagram are its mass, its chemical composition, and its age. The theory of stellar evolution seeks to predict the track the star will follow in the H–R diagram as it evolves, given its initial mass and chemical composition (see Kippenhahn and Weigert 1990 or Hansen and Kawaler 1994). Another property that can affect a star's evolutionary track is its rotation rate, especially when the rotation is rapid.

Stars form through the condensation of interstellar gas by gravitational collapse into 'protostars', somehow shedding angular momentum in the process (for otherwise they would break apart due to centrifugal forces). Once a typical protostar reaches a state of hydrostatic equilibrium, its luminosity is maintained by the liberation of gravitational energy through slow contraction, and energy transport within the star is fully convective. As slow contraction proceeds, the luminosity decreases while the central temperature increases and the star

Table 1.2 *Typical properties of stars on the main sequence*

Spectral class	Mass $M/M_{\odot}$	Radius $R/R_{\odot}$	Luminosity $L/L_{\odot}$	$B - V$	T_{eff} (K)
O5	58	14	800 000	−0.32	46 000
B0	16	5.7	16 000	−0.30	29 000
B5	5.4	3.7	750	−0.16	15 200
A0	2.6	2.3	63	0.00	9 600
A5	1.9	1.8	24	0.15	8 700
F0	1.6	1.5	9.0	0.33	7 200
F5	1.35	1.2	4.0	0.45	6 400
G0	1.08	1.05	1.45	0.60	6 000
G2	1.0	1.0	1.0	0.64	5 780
G5	0.95	0.98	0.70	0.68	5 500
K0	0.83	0.89	0.36	0.81	5 150
K5	0.62	0.75	0.18	1.15	4 450
M0	0.47	0.64	0.075	1.41	3 850
M5	0.25	0.36	0.013	1.61	3 200

develops a radiative zone that grows outward from its centre. Eventually, provided the mass of the star is greater than about 0.1 $M_{\odot}$, the central temperature and density reach the point where the thermonuclear fusion into helium begins and soon takes over from gravitational contraction as the primary energy source. At this point, the star begins its long life on the main sequence, and all the stars of different masses but at this same stage of evolution are said to define the *zero-age main sequence* (ZAMS). Many observed stars are known to lie along pre-main-sequence evolutionary tracks, especially the so-called T Tauri stars, which may be associated with proto-planetary accretion discs.

Stars spend a large fraction of their lifetime on the main sequence, during which they are sustained by the fusion of hydrogen in their cores and move only slightly away from their ZAMS position on the H–R diagram. Table 1.2 lists typical properties of stars of different spectral types on the main sequence (luminosity class V). Note that the radius, luminosity, effective temperature and spectral class of a star of a given mass all vary over the star's lifetime on the main sequence: these variations are small for the lower-mass stars but are significant for the higher-mass stars (e.g. radius and luminosity can vary by as much as 20–30%).

Along the main sequence, stars of greater mass have higher central temperature but lower central pressure and density, and as a consequence, high-mass and low-mass stars have quite different structures. For this reason it is convenient to divide the main sequence into an *upper* main sequence (roughly $M > 2\,M_{\odot}$) and a *lower* main sequence ($M < 2\,M_{\odot}$). The high-mass stars evolve faster and thus spend a shorter time on the main sequence, while low-mass stars evolve more slowly, and indeed stars of mass less than about 0.8 $M_{\odot}$ have main-sequence lifetimes greater than the age of the Milky Way and hence have not yet left the main sequence. When a star exhausts the hydrogen fuel in its core, rapid changes ensue and the star moves off the main sequence onto its post-main-sequence evolutionary track, ending up eventually as some sort of degenerate star. Post-main-sequence tracks differ greatly for stars of different masses, involving different fusion reactions in different layers of the star. For example, a star of mass 1 $M_\odot$ depletes the hydrogen in its core in about 7×10^9 years, after which its helium core contracts and becomes degenerate while hydrogen burning takes place in a shell outside the core. When the hydrogen in this shell is mostly depleted, the star evolves up the red giant branch, with a degenerate core and greatly extended convective envelope. Its evolution up the red giant branch ends when helium suddenly begins to burn in the core (the helium flash). Eventually all of its nuclear fuel is exhausted and the envelope is blown off, leaving the core to continue life as a white dwarf.

1.3 Starspots and stellar magnetic activity

1.3.1 The solar–stellar connection

Since the Sun is not unique among stars, we must expect to find signs of magnetic activity in other stars that are similar to the Sun. Although individual starspots cannot be directly resolved, effects that are associated with magnetic activity on the Sun – X-ray and radio emission, Ca II emission, and signs of flaring – can certainly be detected in such stars. These indications are most obvious in cool, late-type stars (of spectral types F, G, K and M), which possess deep outer convection zones. (There is also a group of B and A type stars that can possess very strong magnetic fields, but their behaviour is very different from that of the Sun.) Measurements of Ca II H and K emission from these cool stars show that their magnetic activity decreases with age, and is closely correlated with their rotation rates. Young, rapidly spinning stars are far more active than the Sun.

Ca II emission from a group of these stars has been monitored for almost 40 years at Mount Wilson Observatory (Baliunas *et al.* 1995, 1998). The relative Ca II emission flux S provides a robust measure of activity, and Figure 1.7 shows three very different records of

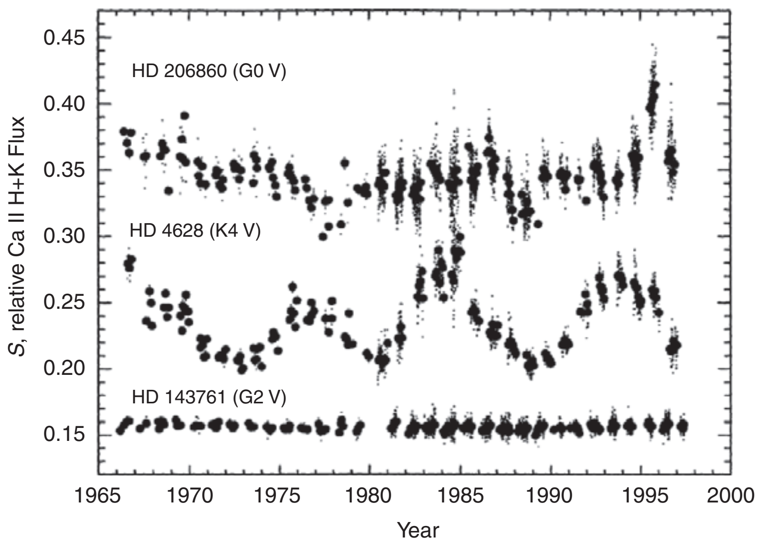

Fig. 1.7. Records of the relative Ca II emission flux S for the very active star HD 206860 (spectral type G0 V), the cyclically active star HD 4628 (type K4 V) and the weakly active star HD 143761 (ρ CrB, type G2 V). (From Baliunas *et al.* 1998.)